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PARTICLE DETECTOR BY MECHANICAL IMPACT SENSING

Michel Benarie, et al

Institut National de Recherche Chimique Appliquee

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If the accelerating capillary is relatively long and the pressure inside the vessel below 1 torr, particulate beams are obtained. They enable the study of particle velocities, their rebound properties, etc. in good conditions. For particulate beam conditions, impact sensing is mass concentration proportional, grain size and substance independent, and sensitivity may rate from the detection of single particle to the range of mg m^{-3}.

With short nozzles and chamber pressure above 1 torr, impact sensing remains possible but marked grain size dependence and possible substance dependence complicate the phenomenon.

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by

Michel Benarie and Jean-Pierre Quetier

Institut Nat'l de Recherche Chimique Appliquee
91710 Vert-le-Petit, France

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Chemistry and Physics Laboratory
Office of Research and Development
Research Triangle Park, N. C. 27711

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Particulate impact is used for the detection and measurement of raindrops and micrometeorites since several decades. Aerosols might be detected in the same way if the suspension is expanded rapidly when it enters through a capillary in a nearly evacuated vessel.

If the accelerating capillary is relatively long and the pressure inside the vessel below 1 torr, particulate beams are obtained. They enable the study of particle velocities, their rebound properties, etc. in good conditions. For particulate beam conditions, impact sensing is mass concentration proportional, grain size and substance independent, and sensitivity may rate from the detection of single particle to the range of mg m^{-3}.

With short nozzles and chamber pressure above 1 torr, impact sensing remains possible but marked grain size dependence and possible substance dependence complicate the phenomenon.

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CONCLUSIONS

The limits and the possibilities of the particulate sensing by mechanical impact were explored.

Three modes of particulate impact sensing were identified :

(1) Impact sensing in particulate beam conditions.

(2) Impact sensing outside particulate beam conditions. This report contains no details about this mode, which has been explored earlier.

(3) Resonant mode impact sensing.

The conditions of the impact sensing in particulate beam conditions are :

(1a)A good focusing of the beam, which can be attained either by a long capillary, or by a succession of shorter ones, separated by fore-pumping chambers.

(1b) A good vacuum in the measuring chamber, of the order of 0.1 Torr or better.

When these conditions are met, impact sensing is grain size and material independent, for hard dusts at least. For sticky, tarry, semiliquid or liquid particles, an influence of the elastic properties of the substance is being felt. The empirical rule is; visible deposit on the impacting surface : dependence on the material. No visible deposit : good mass concentration proportionality.

There are two contradictory requirements for particulate beam conditions : on one hand the diameter of the inlet capillary must be as large as possible, to avoid obstructions by large

particles or by agglomerates; on the other hand, the pumping rate (the dimension of the pumping unit) which has to maintain the working vaccum, must increase with the inlet diameter.

(2) Impact sensing outside particulate beam conditions is not mass-proportional, but may eventually be used in indicating devices with external calibration.

(3a) The resonant mode of impact sensing in mass-proportional under particulate beam conditions.

(3b) Its sensibility is about hundred times (order of magnitude) greater than that of the direct impact sensing. It is reasonable to think, that its sensitivity might be further increased by orders of magnitude through synchronous detection.

(3c) We did not succeed in the technical definition of an easily built resonant mode detector. In each case, hand tuning was employed and such devices seem to be very failure-prone.

RECOMMENDATIONS

Particle detection by impact sensing is a technically feasible proposition.

The transducer aspect of the question, i.e. the transformation of the position of (or of the force exerted on) the impacting surface into an electrical output was not subject to scrutiny.

To obtain particulate beam conditions, which guarantee in most cases for a mass concentration proportional detection, a rather powerful pumping unit must be used. This could be a cost limiting factor of the usefulness of the detector.

A very sensitive mode of detection (the "resonant mode") was discovered. Notwithstanding that the expended man-hours alone on this topic were considerably larger than the total amount of the grant, the detectors on this principle never gave a reliable operation. It could be, that here another, quite promising side-path was discovered. It should be stressed, on basis of our experience, that this is not a quick and easy way for the development of an industrial device.

1. INTRODUCTION

Information about particulates may be obtained through observation their momentum mv (m, mass; v, velocity). That seems obvious and is being already used in two fields for some time: (1) where the particles, as raindrops, have a comparatively important mass and (2) as micrometeorite sensor. Although of slight mass, micrometeorites are moving at very high velocities. (Raindrop detection by purely mechanical sensing : VOEGELMANN, 1913; STRAUB, 1923; by sensing through a microphone membrane : MAULARD, 1951; through piezoelectric sensing: KATZ, 1952; SHVANG and FEDOROV, 1954; WELLHONER, 1960; momentum transducer for sensing micrometeoroid impacts: DUBIN, 1960; ROGALLO and NEUMAN, 1965).

In order to extend the momentum sensing technique to airborne suspended matter, in the range from tenths to tens of micron of diameter, the particles must have high velocities. A convenient way to imprint the needed velocities is to allow the airborne suspension to expand into an evacuated vessel, through a nozzle or a tube. This is a well known procedure to obtain molecular beams since the 1950's (about molecular beams see e.g. ROSS, 1966); when instead of macroions or molecules, particulate matter is accelerated in this manner, "particulate beams" would be a convenient name for the phenomenon.

Particulate beams were observed independently and almost simultanously in two laboratories : by BENARIE (1963, 1964), AVY and BENARIE (1964) and by MURPHY and SEARS (1964). The properties of particulate beams as velocity characteristics, were studied

more thoroughly by ISRAEL and FRIEDLANDER (1967), by DAHNECKE and FRIEDLANDER (1970) and by DAHNECKE and FLACHSBART (1972).

In the paper of AVY and BENARIE (1964) two distinct means are indicated for the detection of particles :

(1) The mechanical sensing of the impacting particles, e.g. by displacement or deformation of a (microphone) membrane. The development and the potential uses of this method will be the main topic of this report.

(2) As the particles are expulsed from a high velocity flow, audible sounds may be produced. This phenomenon was studied and usefully implemented as acoustic particle sensor by LANGER (1965, 1966, 1968 a,b, 1972), by KARUHN (1973) and evaluated by REIST and BURGESS (1968) and by HOFMANN and MOHNEN (1968). Since the effect of the particles is to modify the pressure conditions in a capillary, the pressure differential may be used as on-line concentration monitor, provided the particulate loading is high enough. This variant, oriented rather towards the pneumatic transport of powders was studies by BARTH et al. (1957). The acoustic or pressure-wave mode of detection will not be discussed in this paper.

2. PARTICULATE BEAMS

Raindrop and micrometeorite detection are the proof that impact sensing is perfectly feasible in other conditions than those of particulate beams. Further below, this will be also shown for the case of solid, airborne particulates. Nevertheless, as in particulate beams the geometrical and the mechanical conditions of the process are well defined, they represent ideal means for the basic, quantitative study. To begin with, we shall make a short review of the generation and properties of particulate beams, a topic intimately related to impact sensing.

To obtain particulate beams, the particles must be - as an aerosol or a smoke - initially at or near atmospheric pressure. The aerosol is admitted to the high vacuum vessel through a sequence of individually pumped preliminary chambers that are connected by coaxial capillaries. The capillaries offer almost no resistance to particle flow but substantial resistance to the flow of carrier gas. The particulate beam is mainly confined to a very small solid angle about the capillary axis; approximately one out of ten particles entering the first chamber, with velocity nearly that of the carrier gas molecules, is found in the final beam.

The number of coaxial capillaries might be from one to four; their length/diameter ratio depends on their number (i.e. must be higher in the case of a single capillary and can be around 10 if four capillaries are used) and the available vacuum pumps. Evacuation in several steps - as shown by Fig.1. - has definite

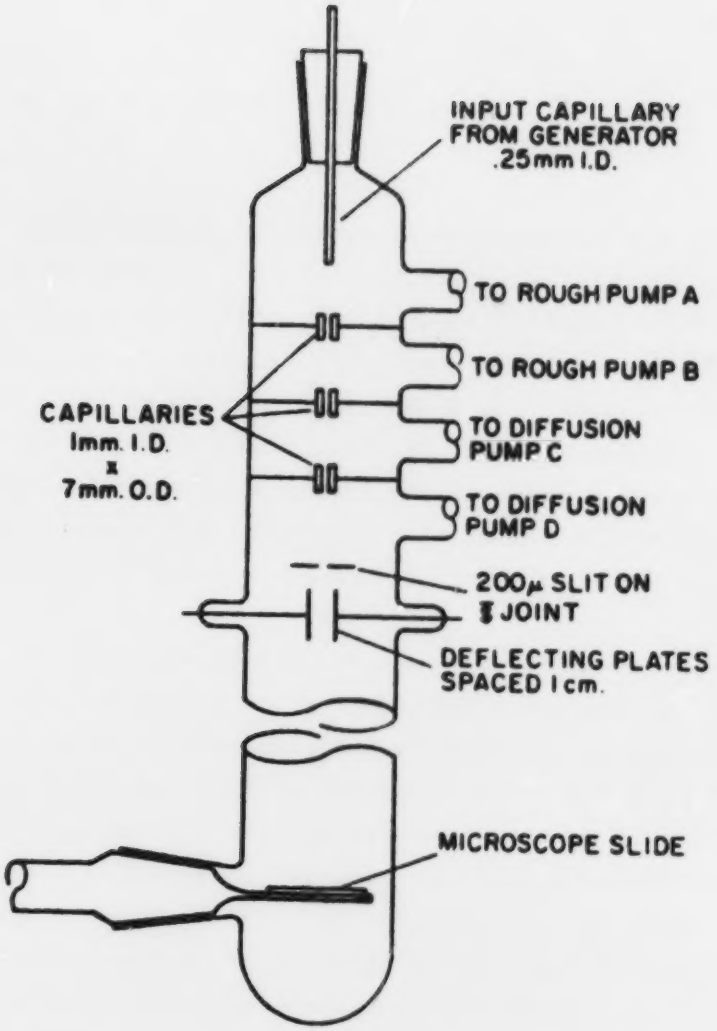

Fig.1 Schematic diagram of a particulate beam source. The smoke generator (not shown) is above the apparatus; the beam is finally defined by the 200 -μ slit in the highest vacuum region. After MURPHY and SEARS (1964)

advantages. MURPHY and SEARS (1964) expanded a mixture of air and molybdenum oxide (MoO_3) smoke at pressure ranging from 50 to 300 mm Hg through a capillary (i.d., 0.25 mm and length, 10 cm) into an evacuated vessel. The core of the beam was passed through three successive capillaries (i.d., 1 mm and length, 2 cm), separating successive chambers, each evacuated by its own pumping system. In the final stage this procedure resulted in a beam of MoO_3 particles expanding into a solid angle of 2.5×10^{-4} steradians (sr.).

The velocity of the particles can be evaluated in several ways: by the "ballistic" method; from the stop distance of the particles or through direct distance/time measurements.

The ballistic method consists in the observation of the downward deflection by gravity, of an originally horizontal beam. Its use (BENARIE 1964, MURPHY and SEARS 1964, ISRAEL and FRIEDLANDER 1967) has shown that following experimental conditions, particle velocities between 20 and 200 ms^{-1} may be observed.

It was established by DAHNECKE and FRIEDLANDER (1970), in accordance with their theoretical prediction, that horizontal particle beams of monodisperse spheres stop in a well defined stop distance and settle to the bottom of the deceleration chamber where a deposit becomes readily visible in a few minutes. It can be shown by an order of magnitude comparison of the horizontal and vertical equations of motion that the trajectory of the beam is effectively horizontal until the particle velocity is very small. The leading edge of the uncollimated beam assumes the form of a parabole (for the larger particles which experien-

ced little Brownian motion while settling) probably resulting from the velocity profile of the carrier gas in the capillary. The length of the deposit varies from a few mm to a few cm as stop distance varies from 10 to 100 cm. The stop distance will be directly proportional to particles diameter and inversely proportional tc deceleration chamber pressure. Measurements of the stop distance will allow to calculate the initial velocity of the particle beam. These conclusions were verified by various experimental results, as shown by Figs. 2 and 3.

Direct measurement of beam velocities was accomplished by DAHNECKE (1971) and HOLLANDER and SCHORMANN (1974a), recording the light signals of single particles which cross two laser beams separated by a known distance. Velocities around 150 ms^{-1} were generally measured.

Other uses than impact sensing of the particulate beams should be mentioned for the sake of record only. They are : (1) Particulate spectrometry, i.e. separation in size classes : BENARIE (1964), DAHNECKE and FLACHSBART (1972); (2) study of the elastic rebound properties of particles and their capture by surfaces at high velocities (for more details, see sect. 6. of this report).

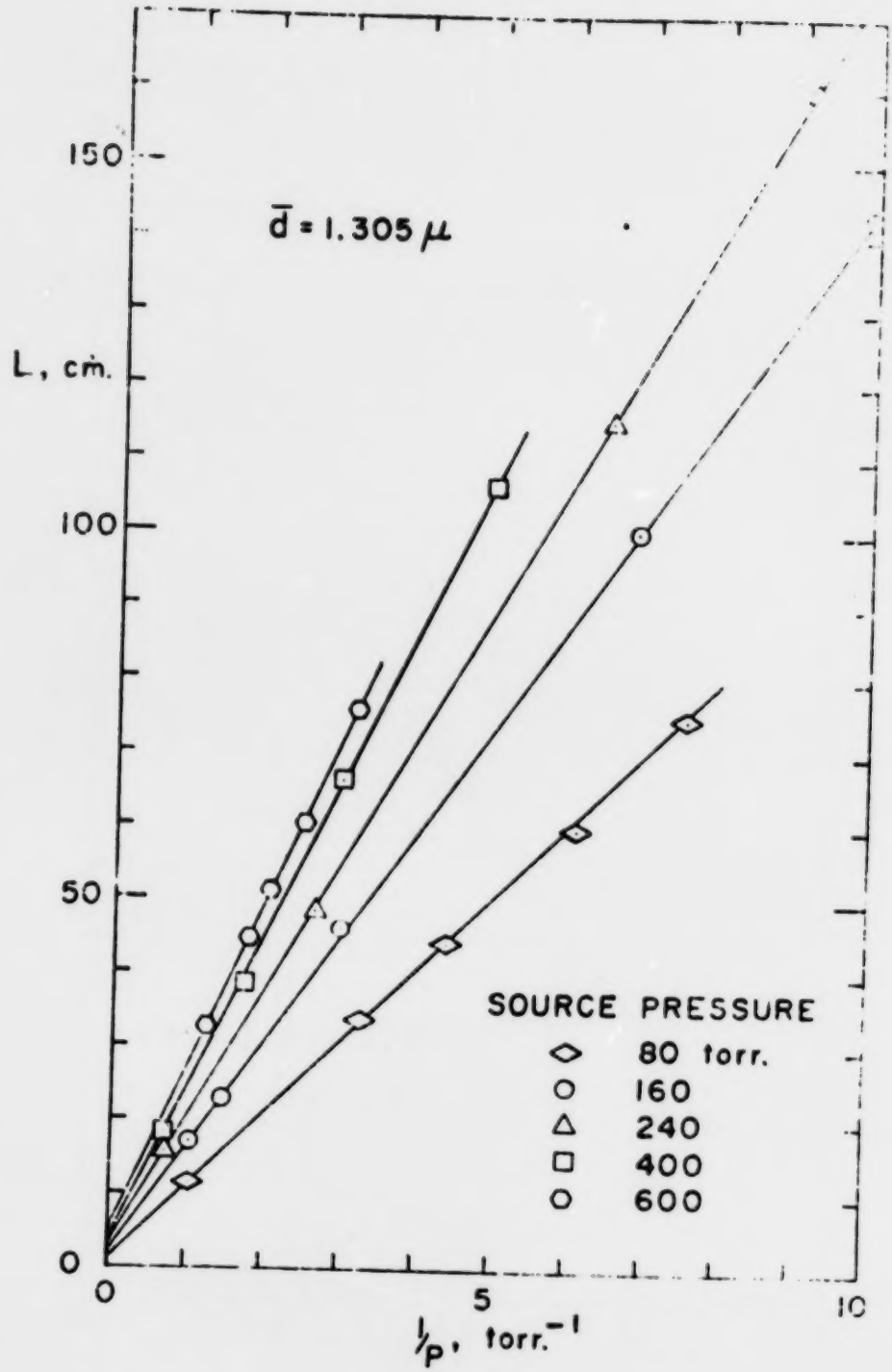

Fig.2 Measured stop distance vs. reciprocal pressure. After DAHNECKE and FRIEDLANDER (1970)

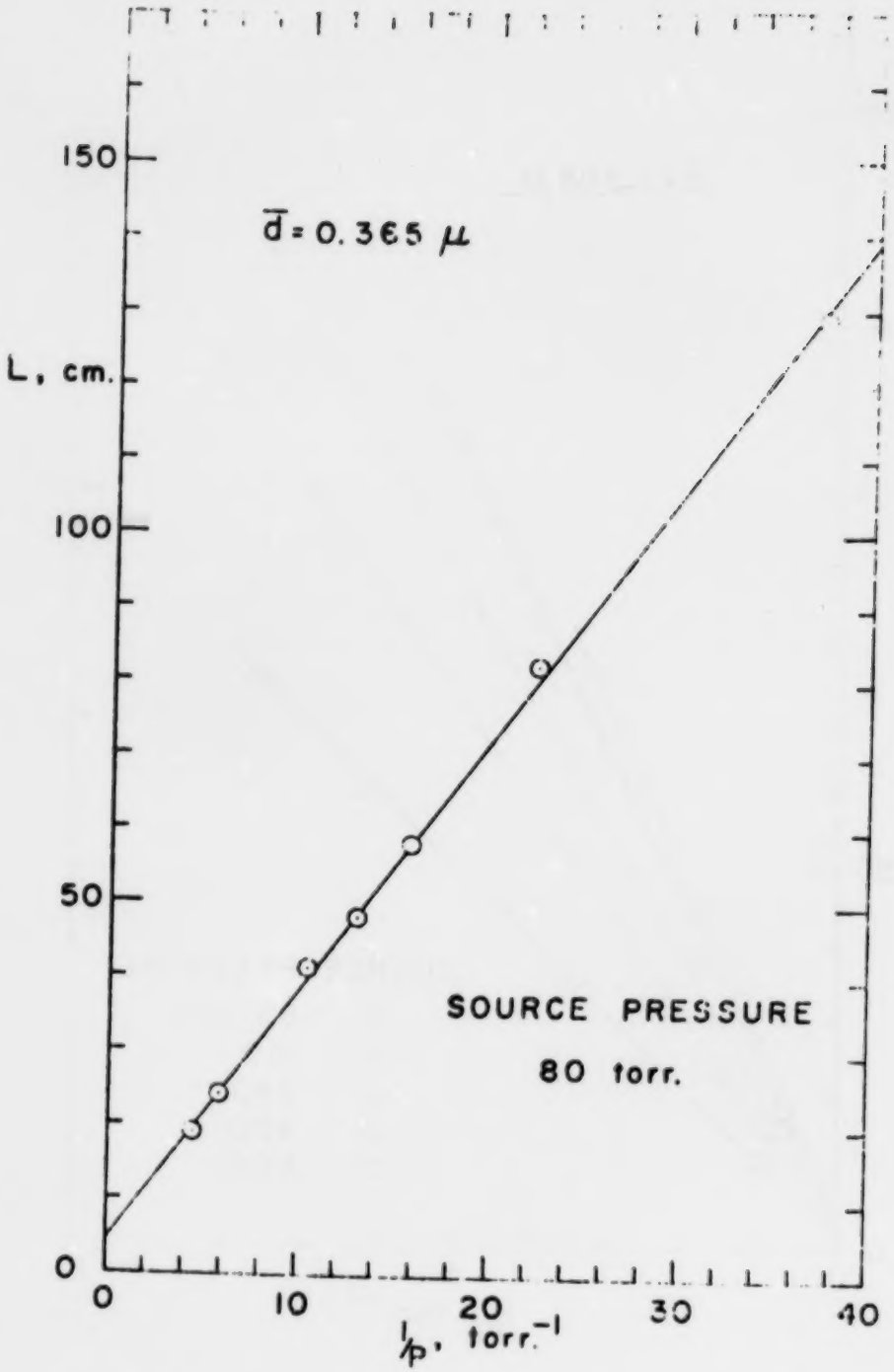

Fig. 3. Measured stop distance vs. reciprocal pressure. After DAHNECKE and FRIEDLANDER (1970)

3. PARTICULATE BEAM IMPACT SENSING

3.1 - THEORY

The reponse of a transducer (membrane, flexible beam or similar device) to an impact is available to simple analysis if the duration of impact t_i is short as compared to the natural period of the transducer $2\sqrt{\frac{M}{K}}$, the natural period of the undamped spring-mass system (K = spring constant (force/length); M = total mass (mass)).

If the system is lightly damped, the mass of the impacting particle m is much less than the mass of the target M; and if the support to which the "spring" links the target has infinite mass then an impact will transfer momentum to the target, according to the equation

$$MV = kmv \qquad (1)$$

V = target velocity

k = momentum transfer parameter; its value is unity for completely inelastic impact and 2 for completely elastic impact.

The kinetic energy imparted to the system is $1/2\ MV^2 = 1/2kmv^2$. If one assumes no internal loss in the system then at the peak of deflection the kinetic energy is converted to potential energy

$$1/2Kx_o = 1/2kmv^2 = \frac{M^2V^2}{2M} \qquad (2)$$

x_o = maximum displacement of the mass.

Solving Eq. (2) for x_o, we have

$$x_o = \frac{MV}{\sqrt{KM}} \qquad (3a)$$

or in terms of the particle momentum

$$x_o = \frac{kmv}{\sqrt{KM}} \qquad (3b)$$

It can be seen from Eqs. (3a) and (3b) that the peak deflection is directly proportional to the particle momentum. Following the peak deflection, the system will oscillate in a decaying sinusoidal transient with the equation of motion

$$M \frac{d^2x}{dt^2} + C \frac{dx}{dt} + Kx = f(t) \qquad (4)$$

C = damping coefficient ((force/time)).

The solution of Eq.(4) shows that for an impulse the maximum amplitude of the envelope of the decaying exponential is directly proportional to the input momentum.

3.2 - SINGLE PARTICLE DETECTION BY SCHORMANN (1974a)

The single particle experiment was realized by HOLLANDER and SCHORMANN (1974a) : a typical recording of their oscilloscope output can be seen in Fig. 4.

3.3.1 - Continuous concentration monitoring - general and theoretical part.

The opposite extreme to the particle by particle impact is the case when their arrival in the beam appears like a continuous jet. The number of particles hitting the obstacle per time unit is very high and the frequency of the impacts is higher by orders of magnitude than the resonant frequency of the receiving surface. For this case, the same considerations apply as for the impulse of fluid jets. If the beam carries the mass q per second during the time differential dt, the total mass

$$m = qdt \tag{5}$$

will impact as

$$F = m \frac{dv}{dt} = \frac{m}{dt} \cdot dv = qdv \tag{6}$$

With an impacting jet velocity v and the mean perpendicular rebouncing velocity -kv, the force which acts on the receiving surface will be

$$F = 2kqv \tag{7}$$

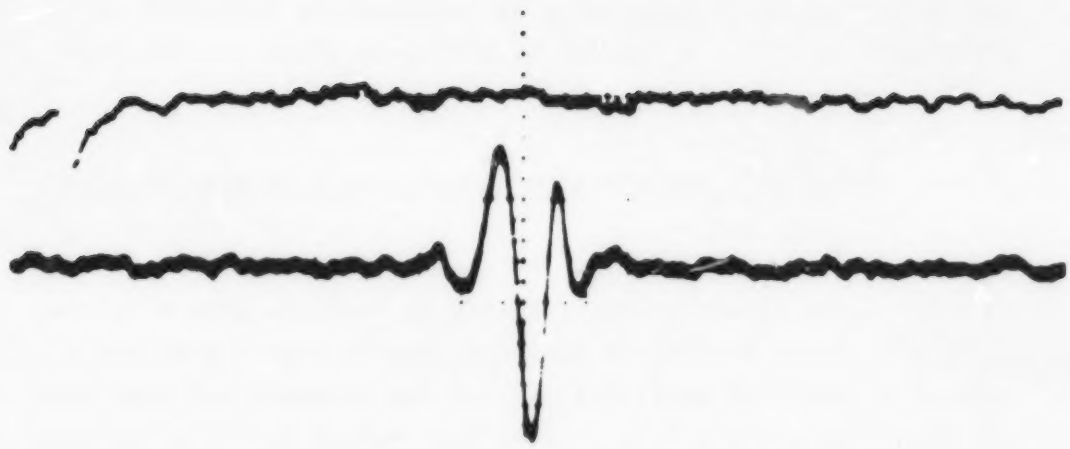

Fig. 4. Oscilloscope display of a 1.84 nm latex particle (lower beam) impacting on a membrane at 180 m s^{-1}. Upper beam : time signals for particle velocity measurement. After HOLLANDER and SCHORMANN (1974a)

Using a sensitive spring microbalance, an air inlet rate of $7.5\ cm^3 s^{-1}$ equivalent to

$$q = \left\{ \begin{array}{ll} 3.75\ 10^{-7} gs^{-1} & \text{at} \quad 50\ mg\ m^{-3} \\ 7.5\ \ 10^{-6} gs^{-1} & \text{at}\ 1000\ mg\ m^{-3} \end{array} \right\} \text{source concentration at atmospheric pressure}$$

with silica dust of grain size between 1 and 20 µm, an effective v around 150 ms^{-1}, BENARIE et al. (1973) measured mass-concentration proportional forces between 0.3 10^{-3} and 10^{-2} dynes, with an average error of ± 20 %. The distance of the receiving microbalance plate (impacting surface) was about 10 cm from the inlet capillary and the vacuum chamber pressure around 0.1 torr. Lack of information about the real density of silica particles and the indirect estimation of velocity did not allow an accurate evaluation of k, which seemed to be in the range of 0.5 to 1.0.

3.3.2 - Particulate beam impact sensing - Experimental.

3.3.2.1 - Preliminary experiments.

The preliminary experiments were made with the glass apparatus schematized in Fig. 5. The inlet glass capillary had about 0.25 mm diameter and 6 cm length. The pumping unit (a double-stage rotational roughing pump followed by a ROOTS of 10 l/sec) maintained a chamber pressure of about 0.1 torr. From the particle diameters (silica dust; see grain size distribution in Fig. 6) and the working conditions, it was inferred following DAHNECKE and FRIEDLANDER - (1970) that the impact velocities were around 150 ms^{-1}.

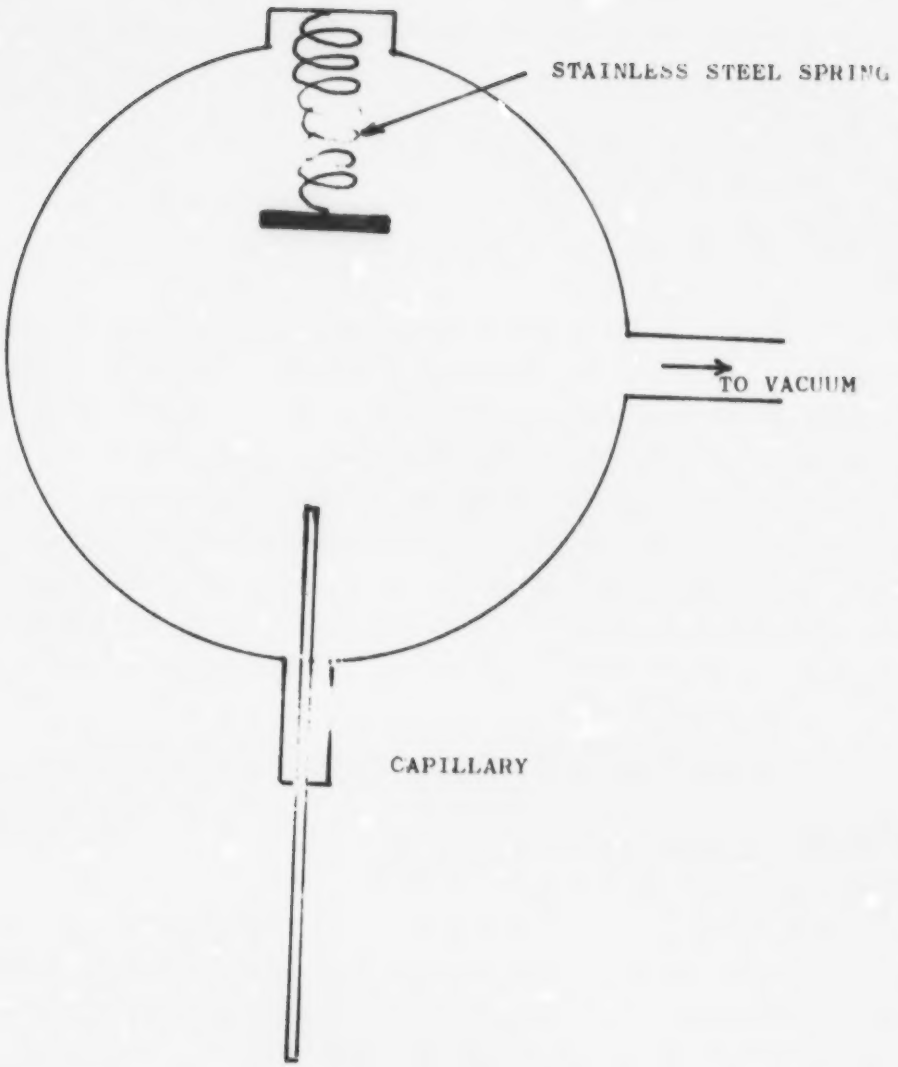

Figure 5. Schematical view of the quartz microbalance impact detection.

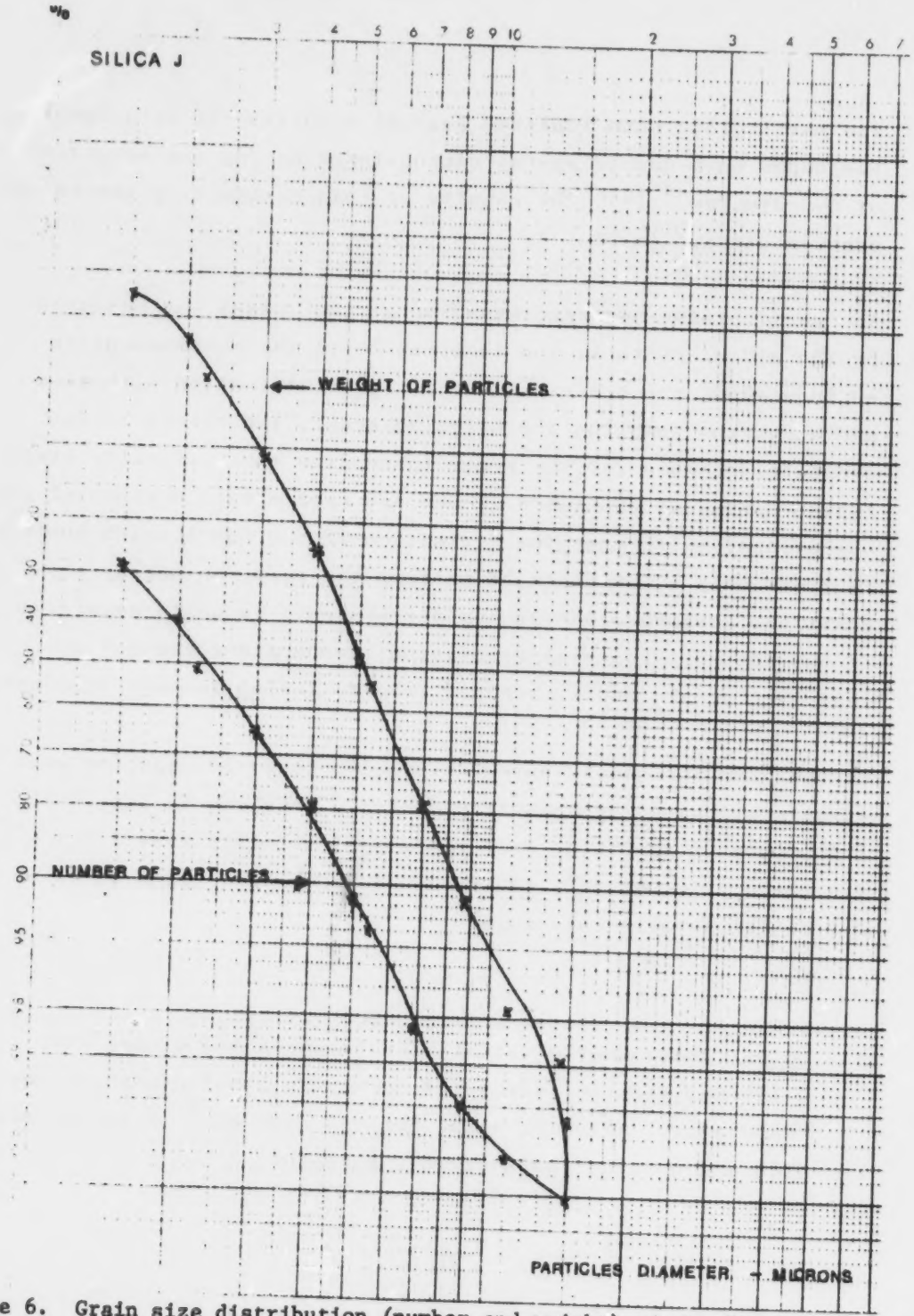

Figure 6. Grain size distribution (number and weight) of the "silica J' test-dust.

The particulate beam impacted against a horizontal mica lamella, suspended on a quartz spiral microbalance having the sensitivity of 0.1 dyne cm^{-1} (*). The results of this preliminary series of experiments are in Fig. 7.

The particulate mass concentration at the intake was measured by the aid of filters. The incertitude in the abscissa gives an idea about the unsteadiness of the concentration with time and about the sampling and weighing error. The spread in the ordinate accounts for the error in reading the vertically oscillating spring microbalance. There are even slight horizontal oscillations, which make the estimation of the equilibrium position at times only a few tenth of mm from the zero, an uneasy proposition. Moreover, the spring microbalance is quite sensitive of outside perturbations (vibration, temperature change) so that little gain could be hoped from following further this path.

On one hand the quartz spiral microbalance is perhaps the most easily calibrated dynamometric device. The slope in Fig. 7 is $2\ 10^{4}$ cm s^{-1}. Admitting that the impact velocity v is 150 m s^{-1}, i.e. $2v = 3.10^{4}$ cm s^{-1}, the value of K See Eq. 7 page 11 is about 0.7, which is quite possible.

(*) Note. These quartz spiral microbalances and others with different caracteristics are currently manufactured in our laboratory, also for sale. The 0.1 dyne cm^{-1} is rather fragile and does not support well shipment.

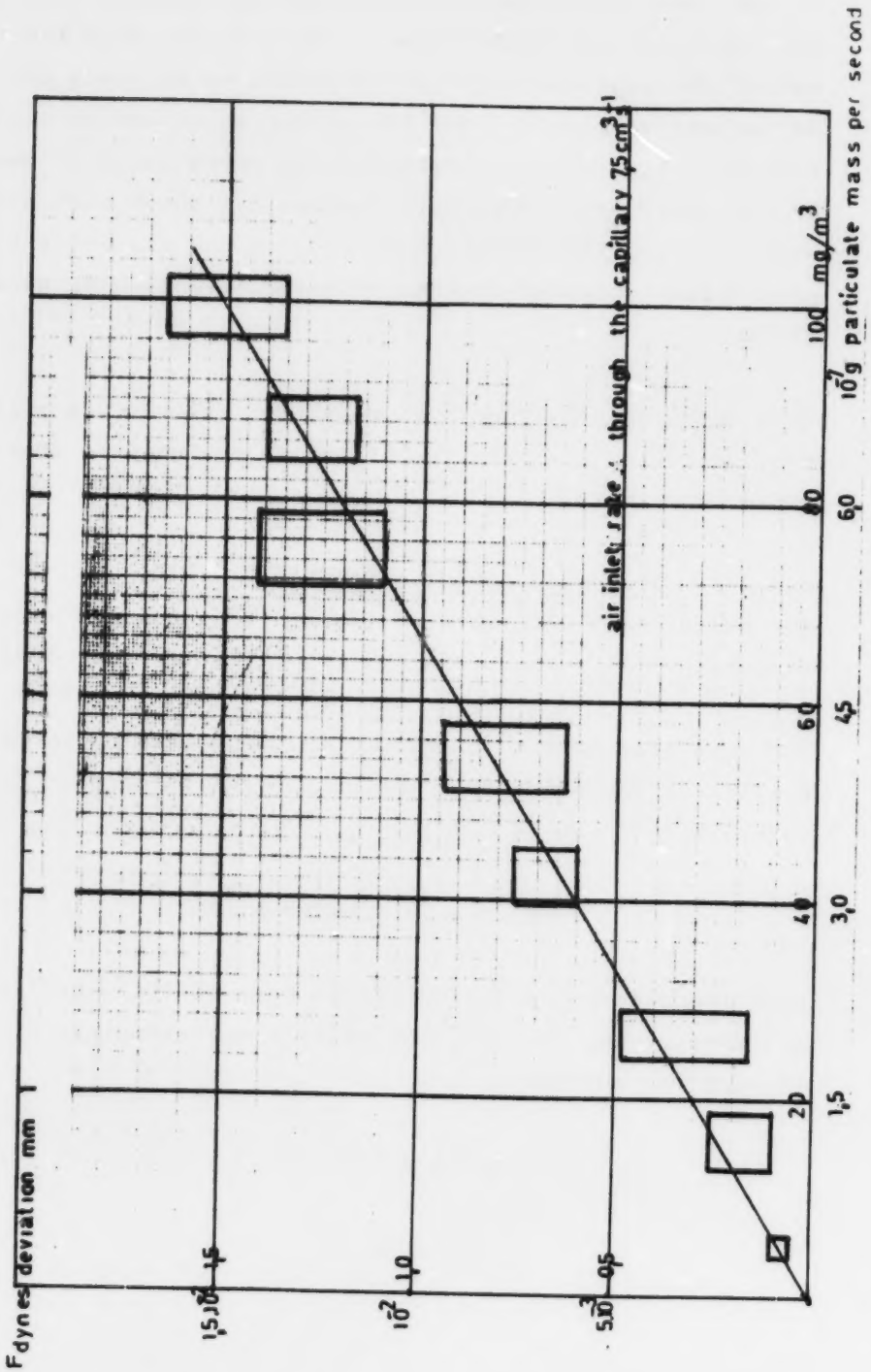

Figure 7. Preliminary results with the spring microbalance detector.

On the other hand, the errors in optical reading of a sensitive micro-balance are rather great. The distance from the inlet end of the capillary must be important as to avoid the influence of the air molecules. Thus the centering of the device becomes critical. Also quite critical is the vibration-free positioning of the instrument. Especially mechanical pumps must not be too near; but too long vacuum manifolds do not allow the high pumping speeds which are needed to maintain molecular beam conditions.

In conclusion, the quartz microbalance detector is a demonstration device at its best. Quantitative evaluations should not be expected from it.

3.3.2.2 - <u>The experimental setup</u>.

The experiments described in the previons section have shown, that Eq.(7) is a fair working formula for further development.

The mass flow q ($g\ s^{-1}$) through the capillary or through the orifice is the product of the concentration c ($g\ cm^{-3}$) by the volume flow Q ($cm^{-3} s^{-1}$):

$$q\ (g\ s^{-1}) = cQ\ (g\ s^{-1}) \qquad (8)$$

with the efficiency f of particle beam hitting the target and considering for the time being k approximately 0,7, from (7) and (8) one has :

$$F = 1.4\ f\ c\ Q\ (gs^{-1})\ v\ (cm\ s^{-1}) \qquad (9)$$

For the order of magnitude f = 1, v = 10^{-4} cm s $^{-1}$ and a particulate concentration

$$c = 1 \text{ g m}^{-3} = 10^{-6} \text{ g cm}^{-3}$$

$$F \approx 1.4\ 10^{-2}\ Q \text{ dynes}$$

One must keep the entering volume flow as high as possible, to arrive at a well measurable dynamometric effect. On the other hand, the chamber working pressure must be below 1 torr (this is an upper limit; it is preferable to work at 0.1 torr) to obtain particulate beam conditions. Expressed the other way round, at a higher pressure, the influence of the molecular air jet on the impaction surface will be too important and introduce perturbations into the measurement of the force exerced by the particulate beam.

With e.g. Q = 10 cm^3 s^{-1} at atmospheric pressure, the volume delivery of the pumping unit must be at or above 100 liters/second, leaks not counted, which is anything but a small pump.

A given volume flow may be either delivered by an orifice in a thin wall, acting as critical orifice or by a capillary of some length. The latter, the capillary, is a good focusing device for the aerosol beam, while in the case of a critical orifice, the particles spread out in a larger solid angle.

The apparatus developed following the conclusions of the preliminary experiments and the above considerations was that presented in Fig. 8 which is approximately on 1 : 1 scale

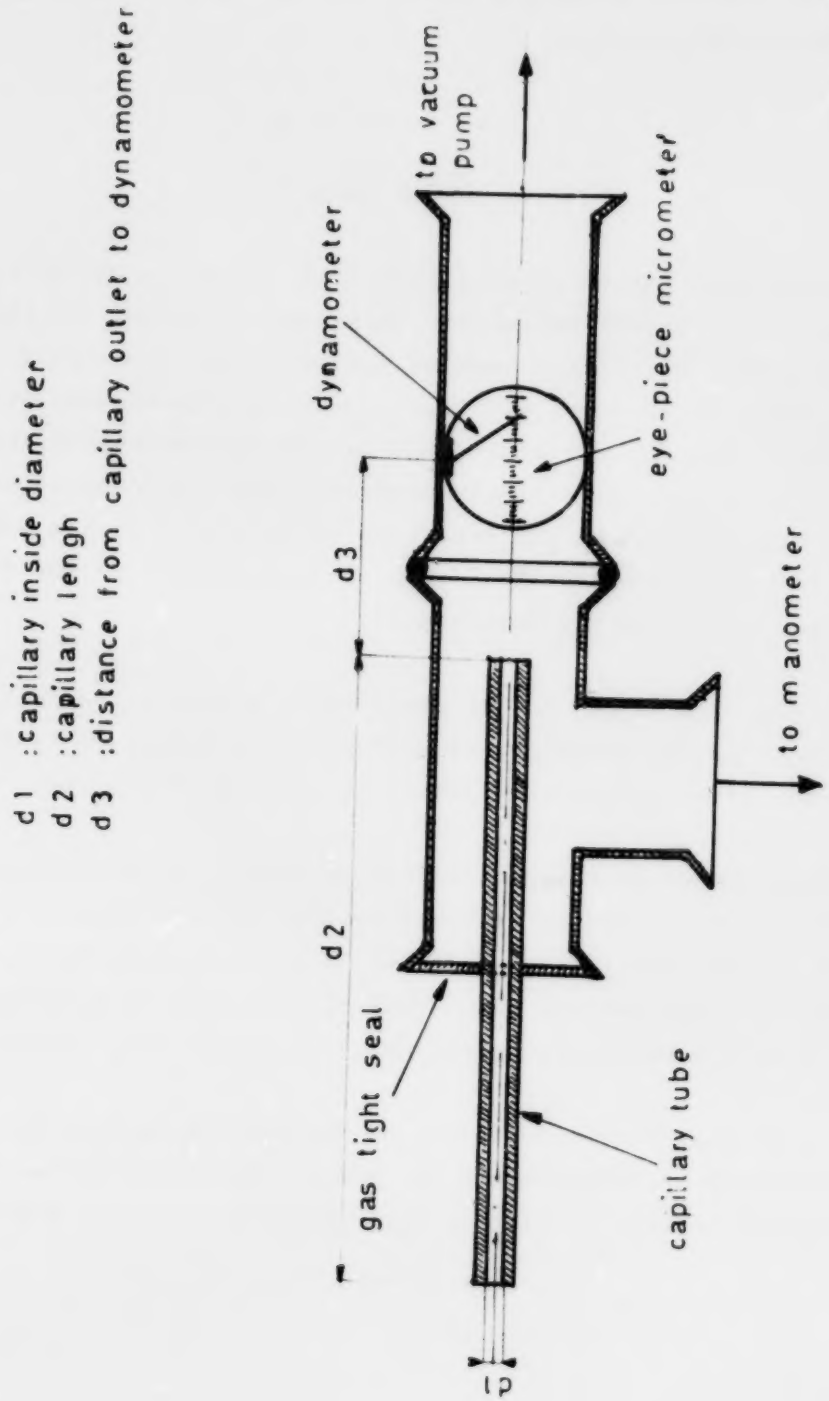

Figure 8. Schematical cutoff of an early version impact detector.

(inner orifices, etc., exagerated for better visibility). As microdynametric device, a vinyl lamella was used, about 0.1 mm thick, approximately of the form of a miniature tennis racket, suspended by its handle. (Calibration of the lamella, see below).

After boosting the aspiration of the vacuum manifold to 300 liters/second, we experimented with different capillary lengths and diameters in view to obtain particulate beam conditions.

With steel capillaries of 0.8 mm I.D. (d3) in Fig.13 of length from 10 to 50 cm, the vacuum did not attain the sought low values. The lowest working pressures were around 1 torr, clearly insufficient, shown also by the fact that even after gradually increasing d_2 (the distance from the and of the capillary to the impacting surface) to 12 cm, an aerodynamic jet influence (fluttering) of the plastic lamella was perceived.

On the other hand, using the silica dust of grain size represented in Fig.6, obstructions of long (i.e. longer than 15 cm) capillaries occured, but were not all too frequent.

After some experiments with 0.6 and 0.5 mm I.D. capillaries, we went over to 0.3 mm I.D. which gave full satisfaction as far chamber vacuum and vibrationless lamella behaviour were concerned. But, in very favorable case, such capillaries gave fifteen minutes obstructionless operation. Mostly even this "limit" was not attained, and after only a few minutes experiments, time-consu-

ming disassembly, cleaning, etc. was needed. Obviously, this is not a good way for accumulating quantitavie results.

After a severalintermediate trials, the arrangement shown in Fig. 9 was adopted. A forepumping chamber was attached before the capillary inlet. A critical orifice of 0.5 mm diameter, at 0.5 cm from the capillary inlet and centered against it, acts as particulate intake. The chamber A was evacuated by a double-stage oil rotation pump of 3 liters/second, but the vacuum here was not measured. A capillary diameter of 0.5 mm and length of 14 cm gave good, obstruction and trouble free performance during the whole series of experiments wich will be described below. The distance d2 from the capillary outlet to the impacting surface was 5 cm.

3.3.2.3 - The yield of the intake.

It was checked and rechecked, that with a single capillary, all the particulates entering the intake, hit the target, within a circle of 5 mm, if the latter was well aligned. So, in the case of the single capillary, f in Eq (9) is unity and dynamical calculations as in sect. 3.1 may be made.

In the case of the setups of Fig.9 - i.e. a the presence of a roughing chamber, f is not necessarily unity and its experimental determination becomes necessary.

The setups used can be seen in Fig.10; it is the same as that which was used for the measurement of the mass-concentration proportionality and will be described with more detail below.

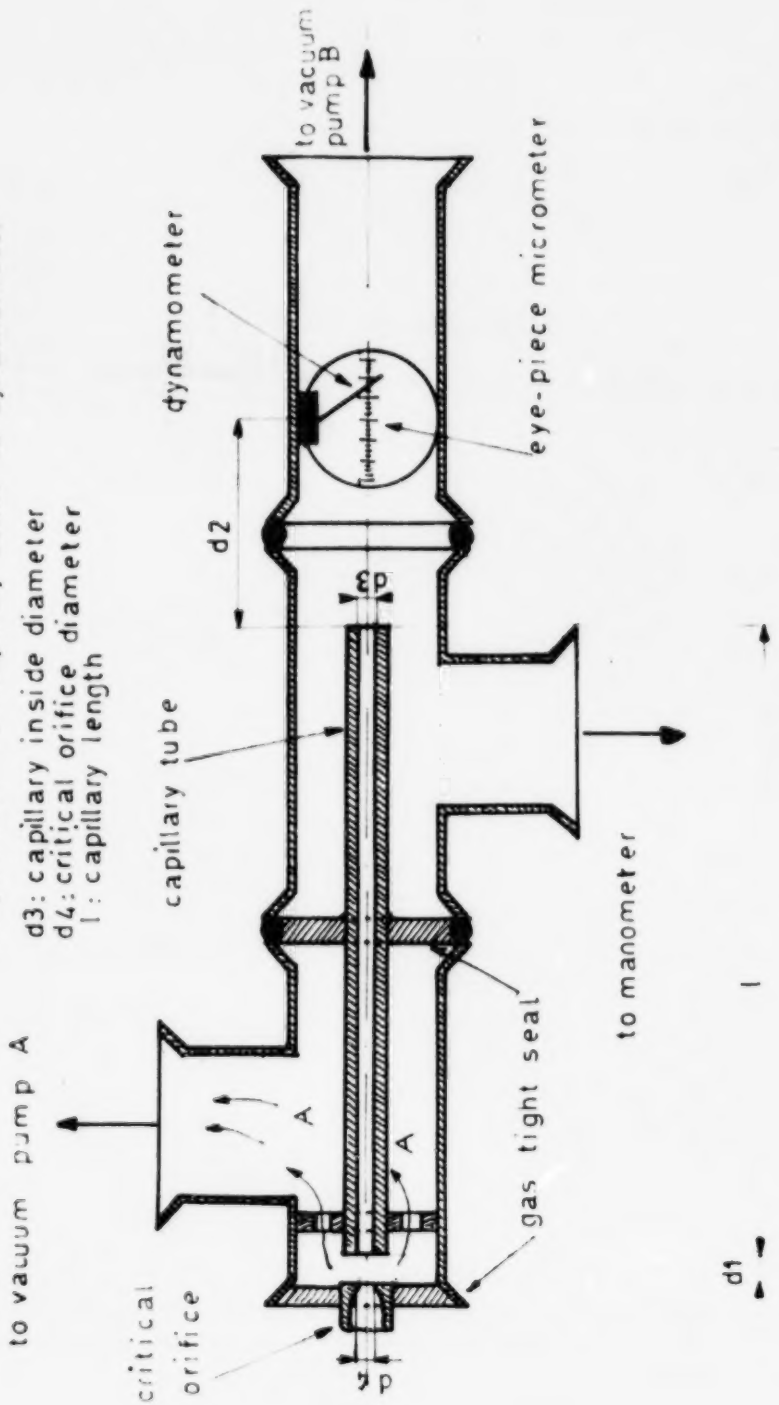

Figure 9. Schematical cutoff of an impact detector with roughing chamber.

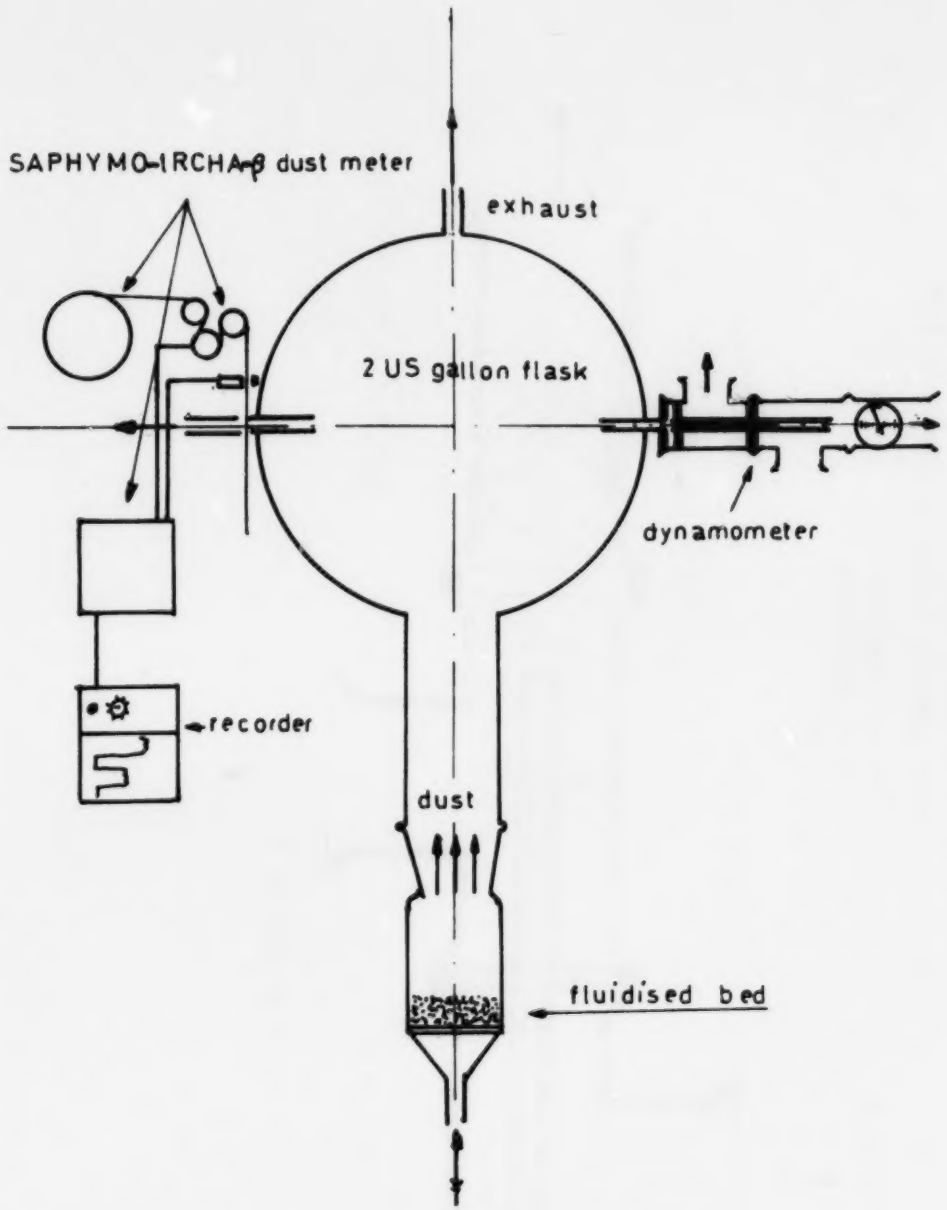

Figure 10. Calibration of the detector with dust dispersed by a fluidized bed; comparison with a β-ray absorption device.

The principle, which is of concern here, consists of coating the impactor surface with a thin layer of sticky silicone grease and feeding into the intake a particulate suspension of known concentration during a measured interval of time. The mass difference of the lamella (impactor surface) before and after the experiment, divided by the actually aspirated particulate mass, gives the intake yield.

On different days, following yields were measured : Table 1

Table 1

Measured yields of the intake of the device illustrated on Fig. 15

Particulate concentration mg/l	115±15	23±4	36±5	10±2	11±2	18±2	26±3
Sampling duration seconds	63± 1	90±1	60±1	300±1	240±1	120±1	90±1
Samples volume liter	1.05±0.03	1.50±0.01	1.00±0.01	3.00±0.01	2.40±0.01	1.20±0.01	1.50±0.01
Particulate mass, in mg	121±19	34±6	36±5	30±6	26.5±5	21.6±2.6	39.0±5
Particulate mass, collected on the target mg	20.2±0.1	8.4±0.1	8.3±0.1	6.5±0.1	5.2±0.1	5.2±0.1	9.0 0.1
Intake yield %	17.2±2.6	27.0±6.0	23.5±3.5	23.2±5.3	20.5±4.2	24.5±3.5	23.5±3.5

The first of these values, around 17 %, is very probably too low because of the thickness of the deposit, some particle rebounce took place. Some of the differences in the span from 20.5 to 27.0 per cent may be real and due to imperfect centering of the pieces after disassembly and cleaning. The major part of the relative error is due to the particulate mass concentration measurement made in this case by weighing of control filters; the estimate of the relative standard deviation for the concentration is 15 %. Taking into account these sources of error, one may estimate the intake yield of the sensor of geometry defined in Fig. 9 at 23 %.

3.3.2.4 - The influence of the grain size distribution.

3.3.2.4.1 - The calibration of the device. The impact-sensing instrument is shown in Fig. 9; it was partly described in the previous section. The inlet is a 0.5 mm dia critical orifice mounted on a rough-pumping chamber A. In its axis, at 5 mm distance is the inlet capillary of 14 cm length and 0.5 mm I.D. The vacuum in the main chamber is maintained as nearly as possible at 0.1 torr. The particle velocities were not directly monitored, but from published evidence it may be inferred, that they were in the 200 to 300 m s^{-1} range. The results shown below prove, that this velocity was uniform for all particle dimensions concerned and did not vary appreciably from one experiment to the other.

At a distance of five cm from the capillary outlet was the impaction sensing lamella. This was cut out from vinyl foil 0.03 mm thick, a circle about 12 mm diameter with a "handle" of 3 mm width.

The dynamometric calibration of the lamella was done in the following way : the apparatus in fig.9, normally used in the horizontal position, as shown, was set up vertically, i.e. the lamella horizontally. The lamella remained perpendicular to the tube axis, which showed that its weight represented but a negligible fraction of the elastic restoring force of the "handle", which acted as a beam fixed at one of its ends. Microanalytic weight pieces (platinum wire) were charged as near as possible to the center of the circular receptor surface and the deflections observed on the eye-piece micrometer of a long objective working distance microscope . Four such points, gave a straight dynamometric calibration curve, provided that the deflections were kept below 10°. This was attained by chosing the appropriate "suspension beam" width, as the thickness was already given by the vinyl sheet.

As already explained, the impact measuring device was used with its axis horizontal, i.e. the lamella pending. A zero-deflection was observed, i.e. a deflection from the vertical, partly due to the laminating tensions sometimes present in the lamella, and partly to the air jet as the pumps were on. This deflection is shown in an exaggerated way on Fig.9. Due to this deflection, the impact of the particulate beam was not perpendicular to the lamella. If the receiving surface deviates from the vertical by α degress, the flexing force is proportional to $\cos \alpha$. The appropriate correction to the readings was applied when $\alpha > 10°$; below this limit, the correction factor is less than 1.5%, which is certainly below the precision of the measurement.

Strictly speaking, in case of angular deviation from the vertical, the restoring momentum of the pendulum formed by the lamella should also have been considered. But, as it was already exposed when speaking about calibration, the weight of the lamella may be neglected before the elastic force; thus this correction was not applied to the data.

3.3.2.4.2 - Results : grain size independence. The apparatus used for the measurement, is schematized in Fig. 10. A fluidized bed, containing 0.3 mm dia glass beads and the test dust, generates the particulate cloud. The intakes of the impact sensing device and of a SAPHYMO-IRCHA β - absorption dust monitor, operating in the 1 minute sampling mode are horizontal and about 10 cm distant inside a 10 liter flask. The position of the impact-sensing lamella is read microscopically.

The following hard test-dusts were used :

Silica, density 2.7, grain size distribution Fig.6

Aluminium oxide, density 3.6, grain size distributions Figs. 11 and 12.

Silicon carbide, density 3.2, grain size distributions, Figs. 11 - 20.

A summary of the results is shown in Fig. 21. Here three particulates as different in grain size as possible (silice J Fig. 6 Aloxite 40 Fig. 11 and silicone carbide W25, Fig. 19)

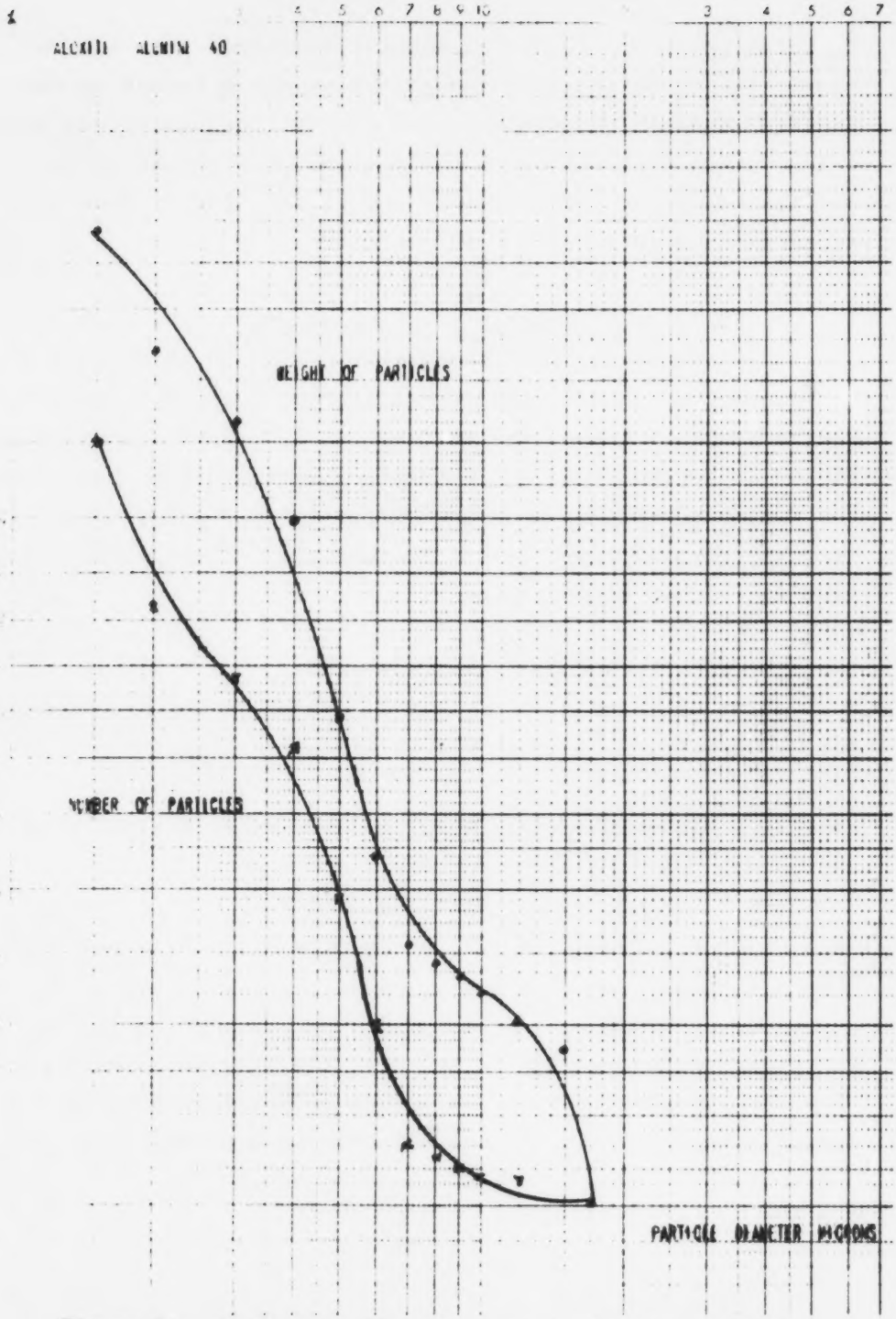

Figure 11. Grain size distributions (number and weight) of the test dusts.

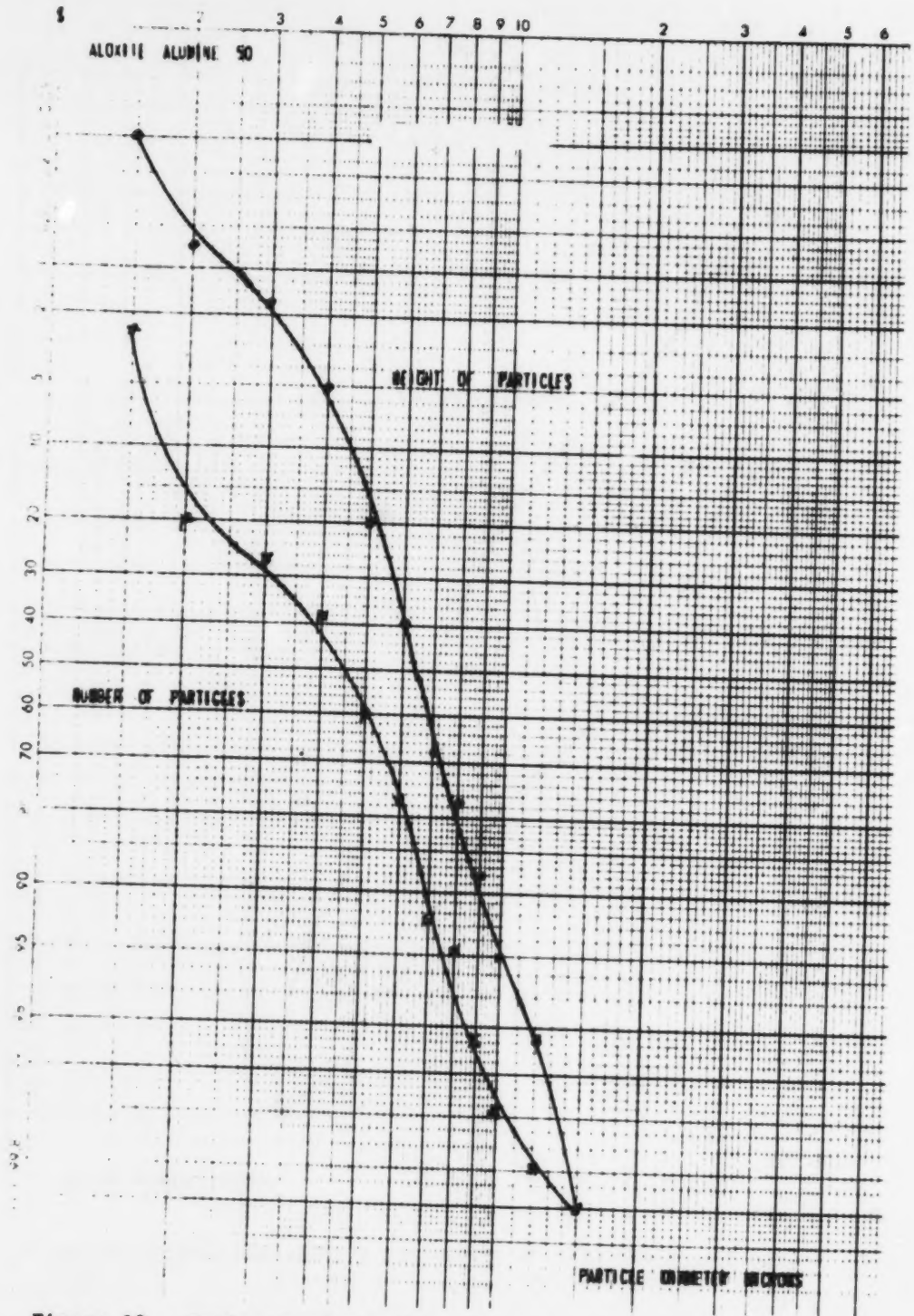

Figure 12. Grain size distribution (number and weight) of the test results.

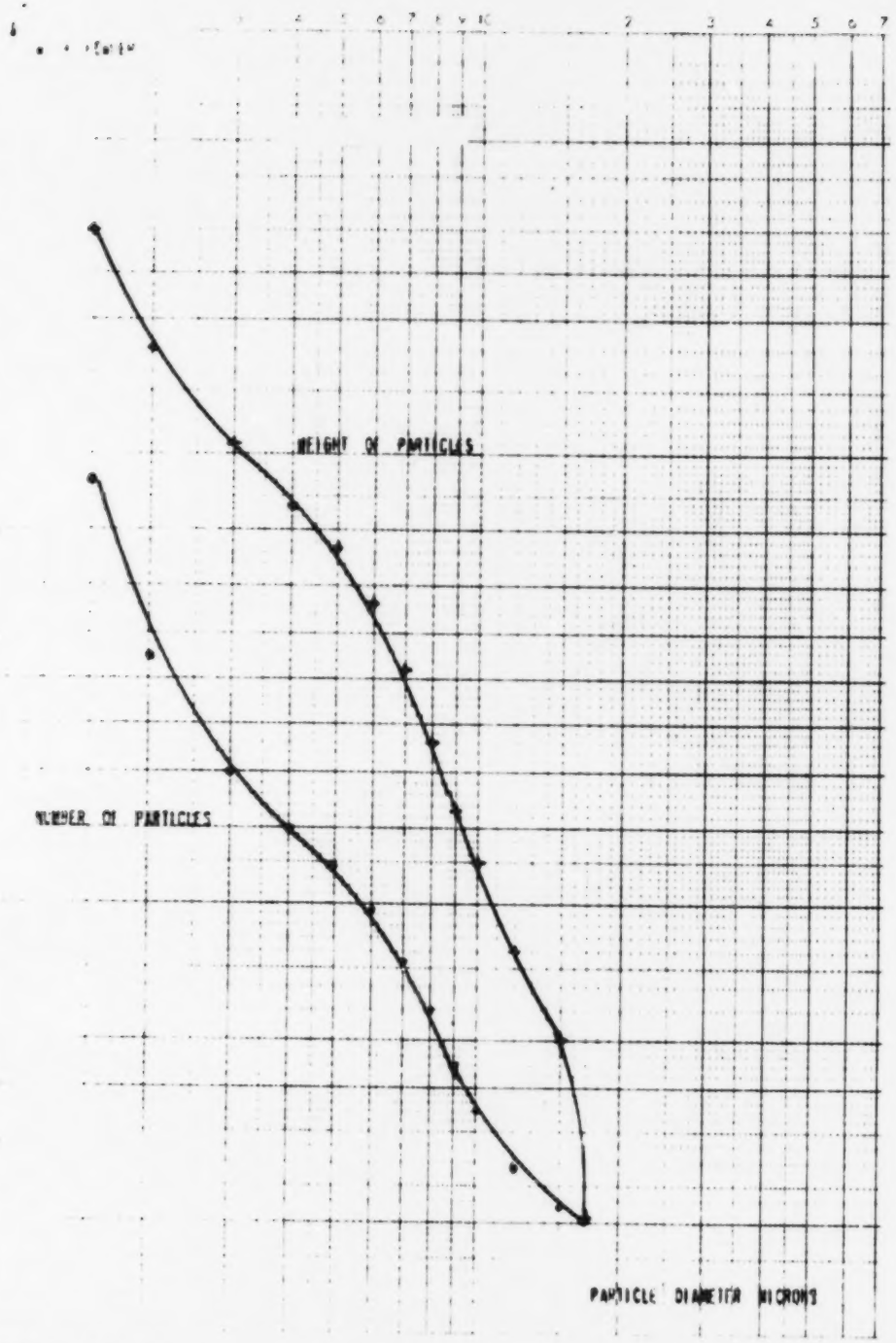

Figure 13. Grain size distributions (number and weight) of the test results.

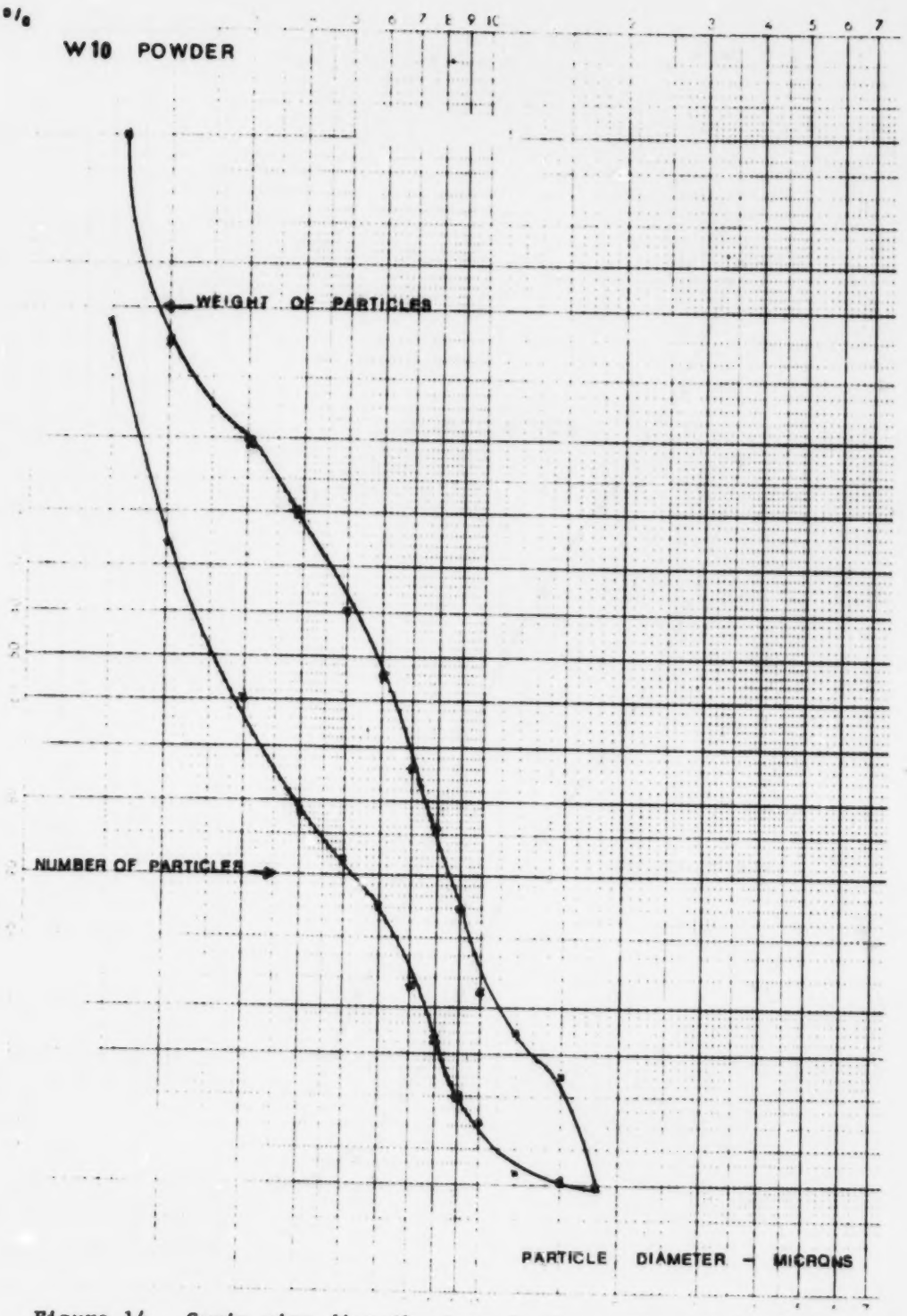

Figure 14. Grain size distributions (number and weight) of the test results.

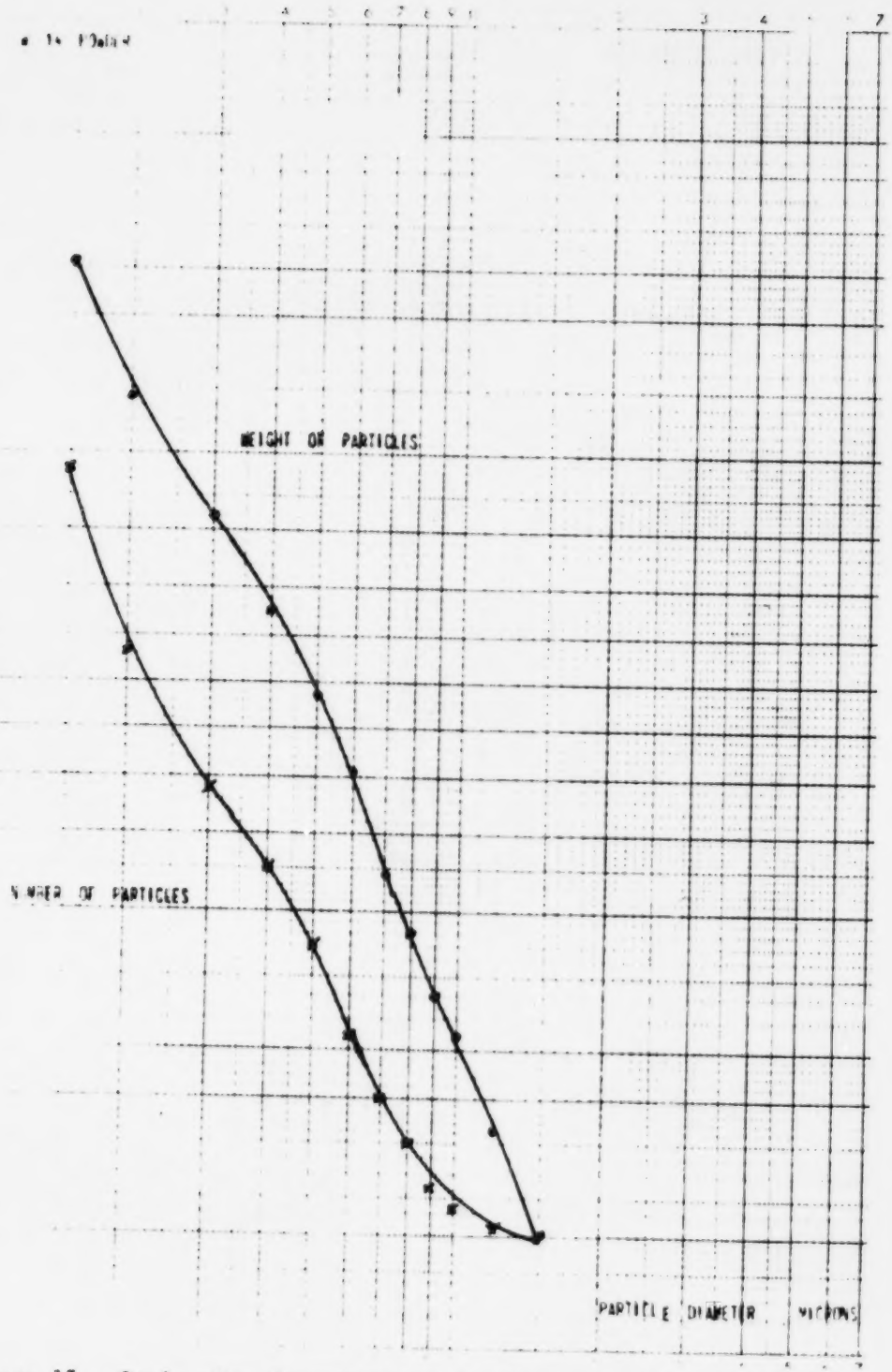

Figure 15. Grain size distributions (number and weight) of the test results.

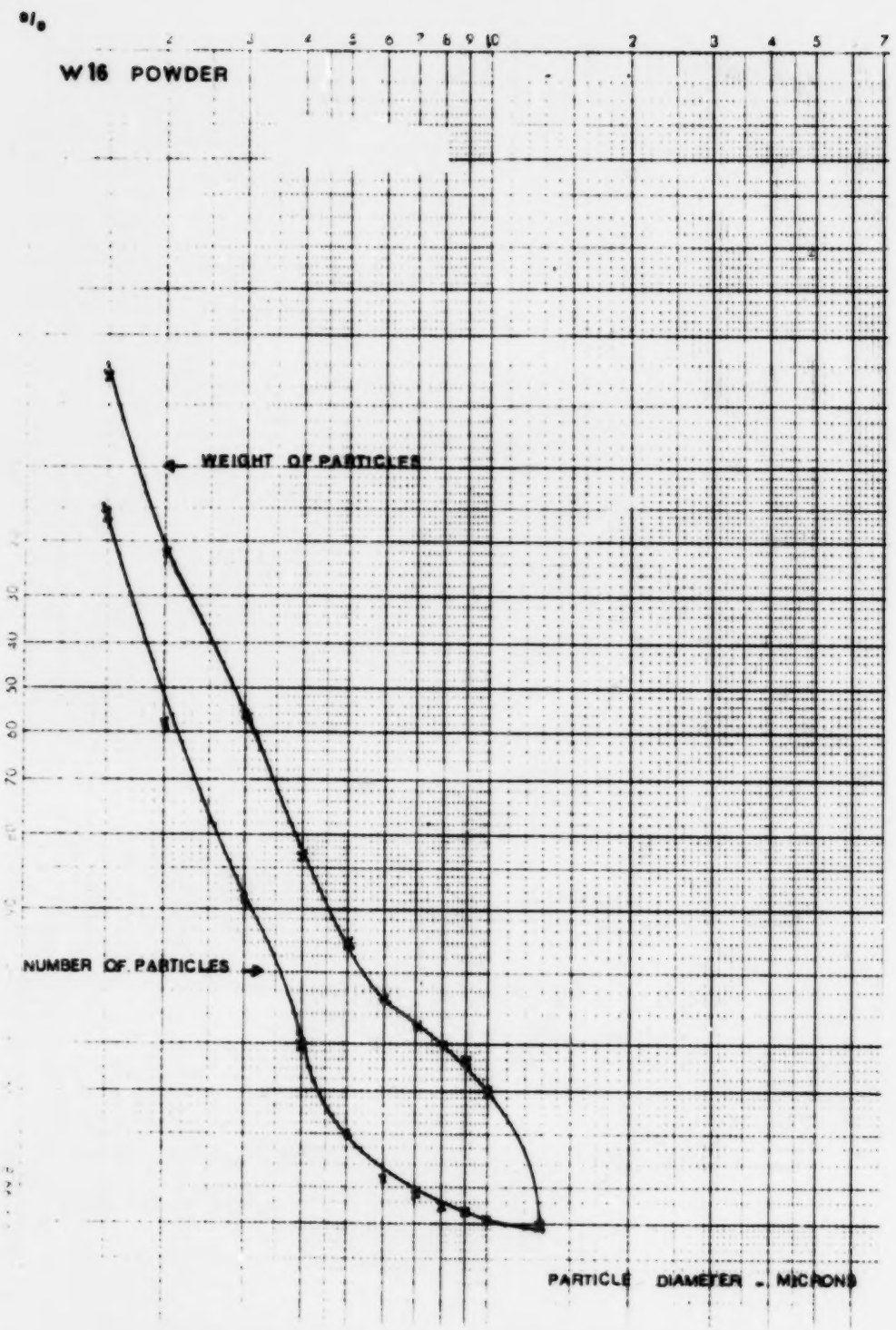

Figure 16. Grain size distributions (number and weight) of the test results.

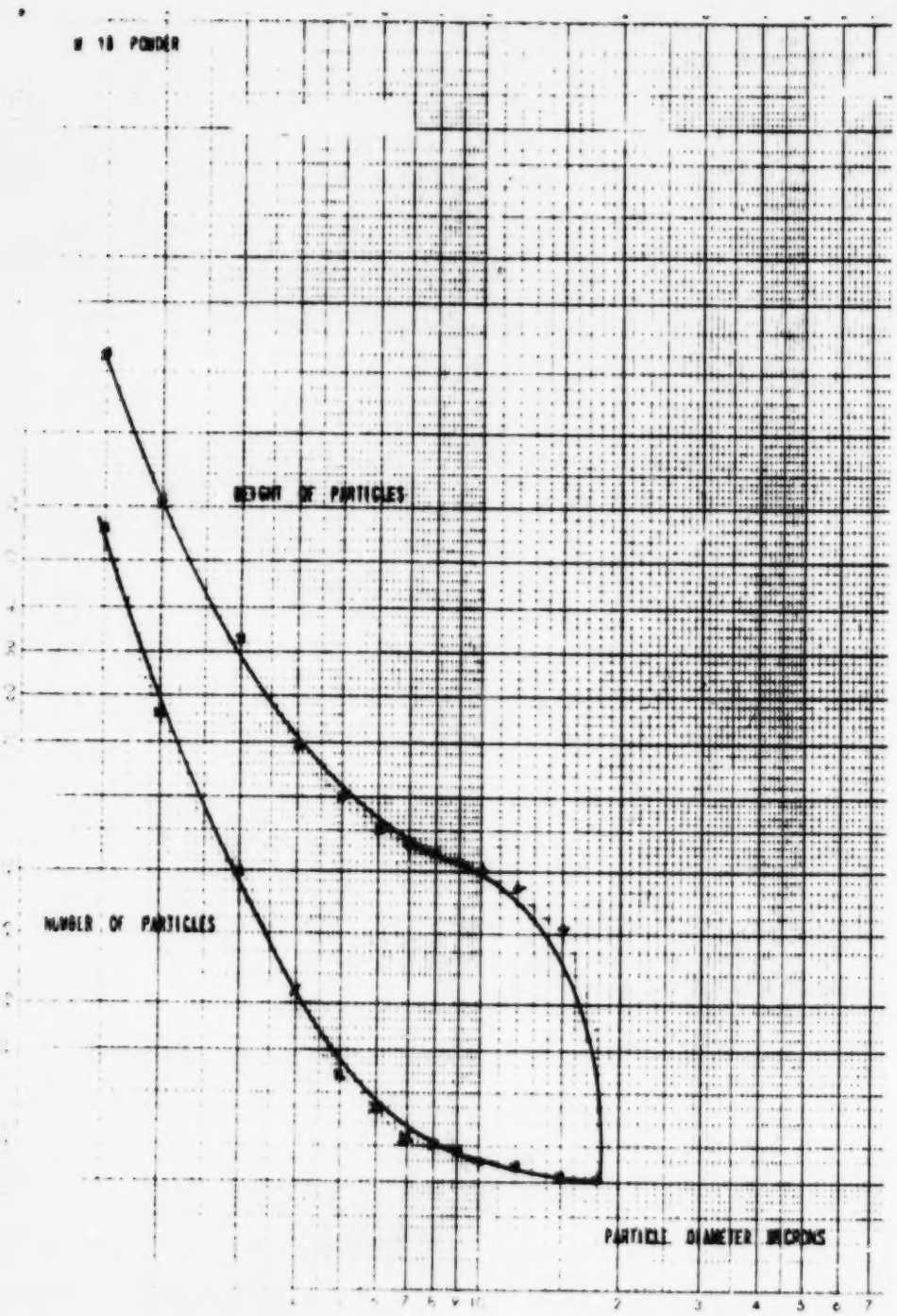

Figure 17. Grain size distributions (number and weight) of the test results.

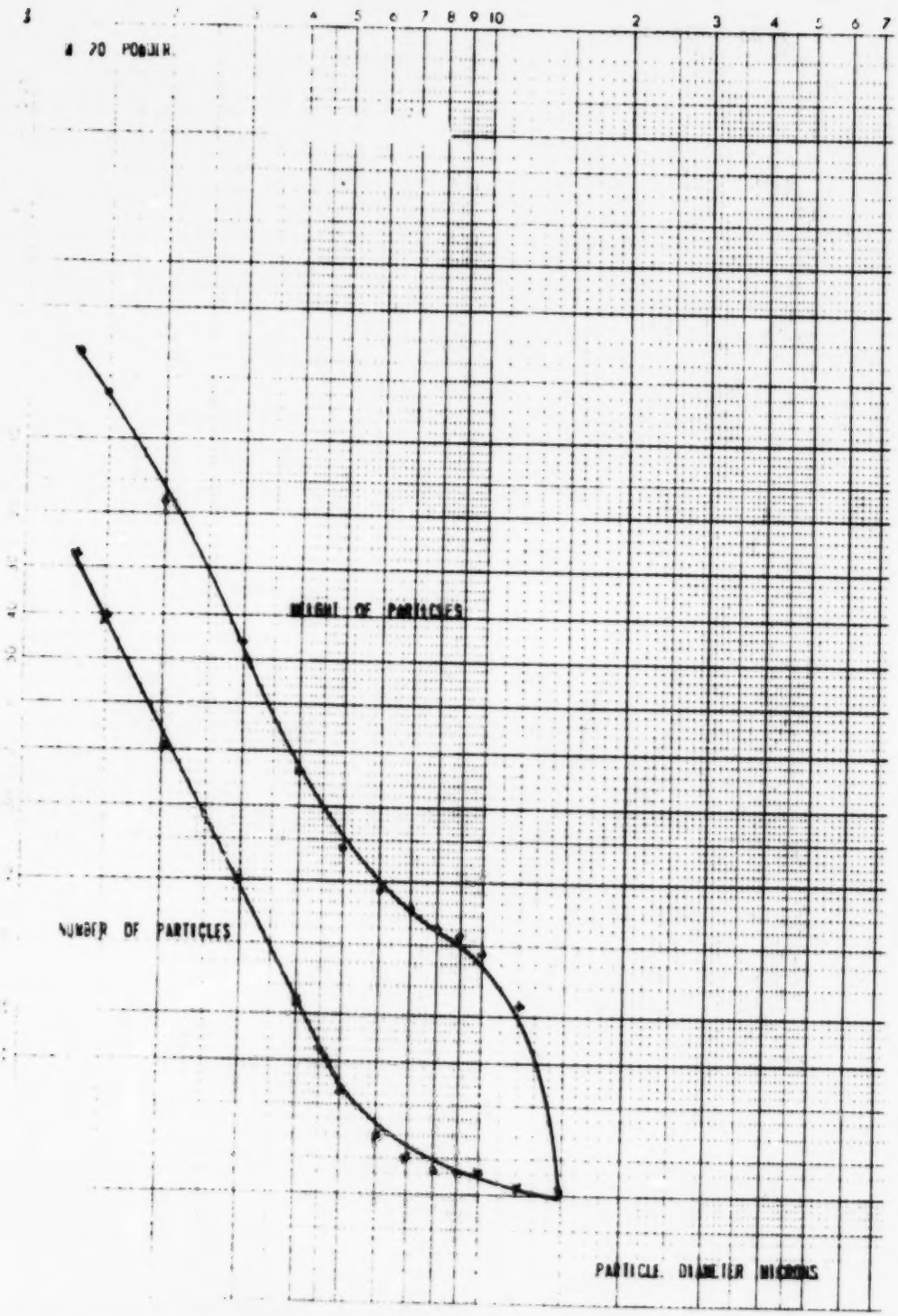

Figure 18. Grain size distributions (number and weight) of the test results.

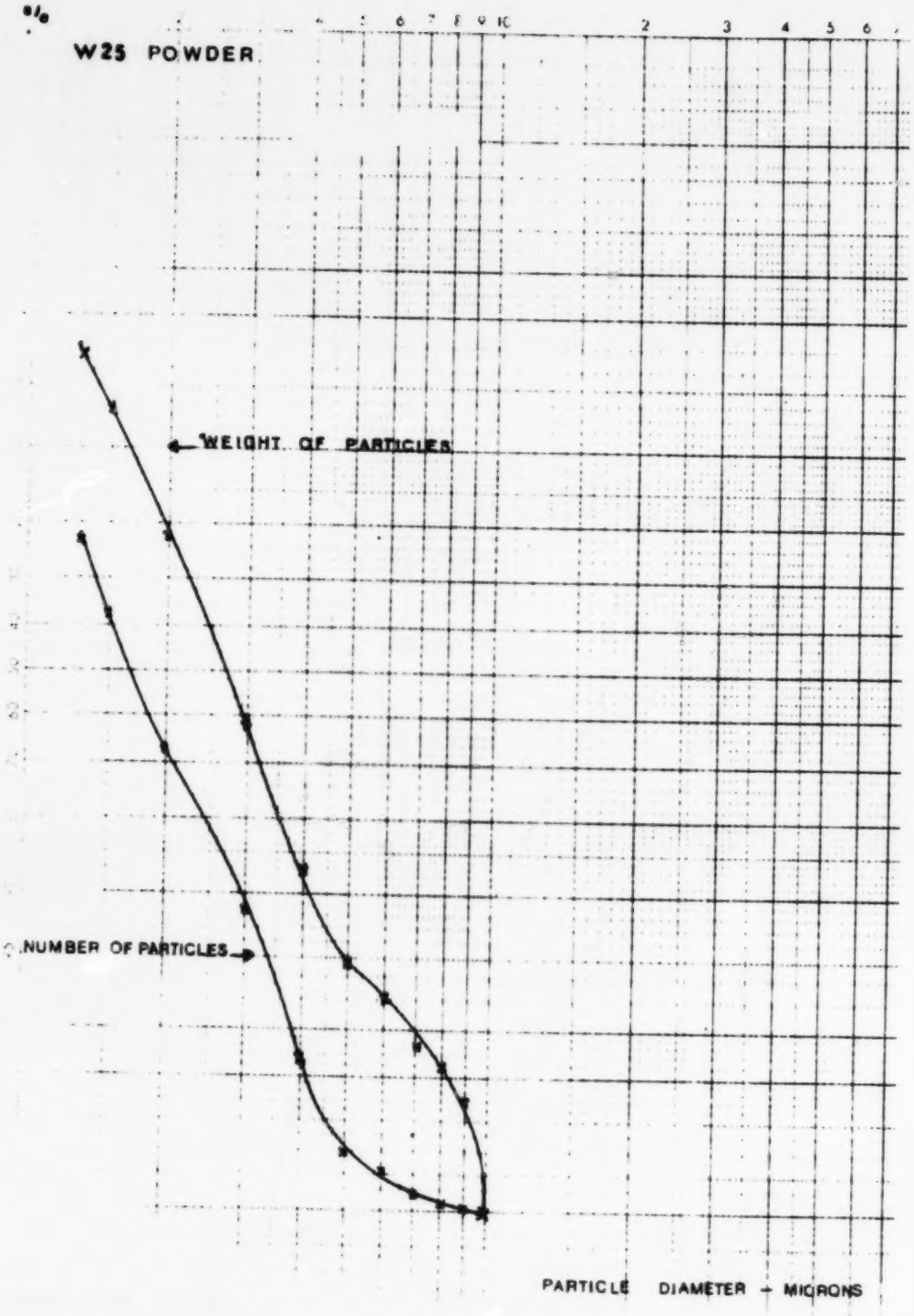

Figure 19. Grain size distributions (number and weight) of the test results.

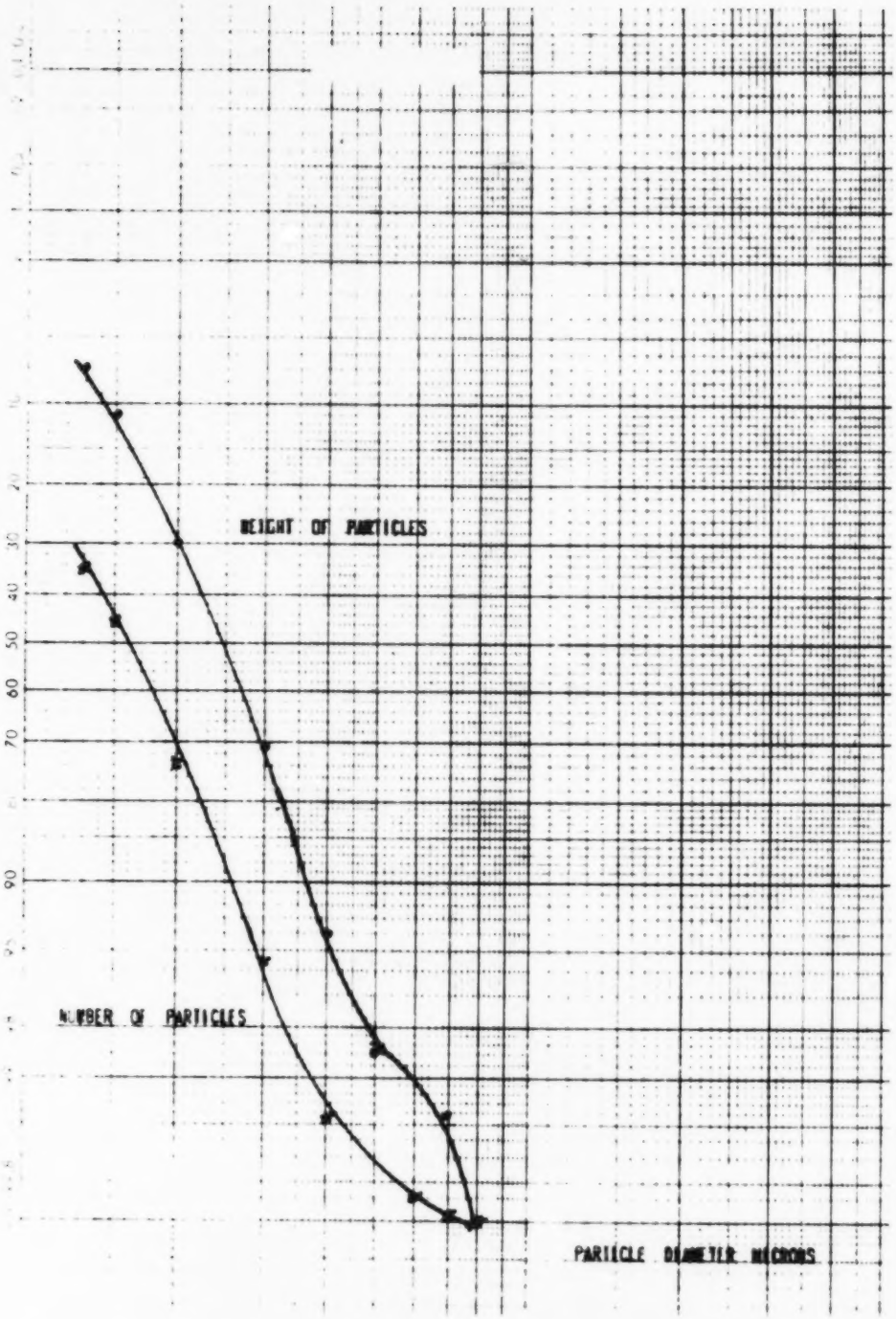

Figure 20. Grain size distributions (number and weight) of the test results.

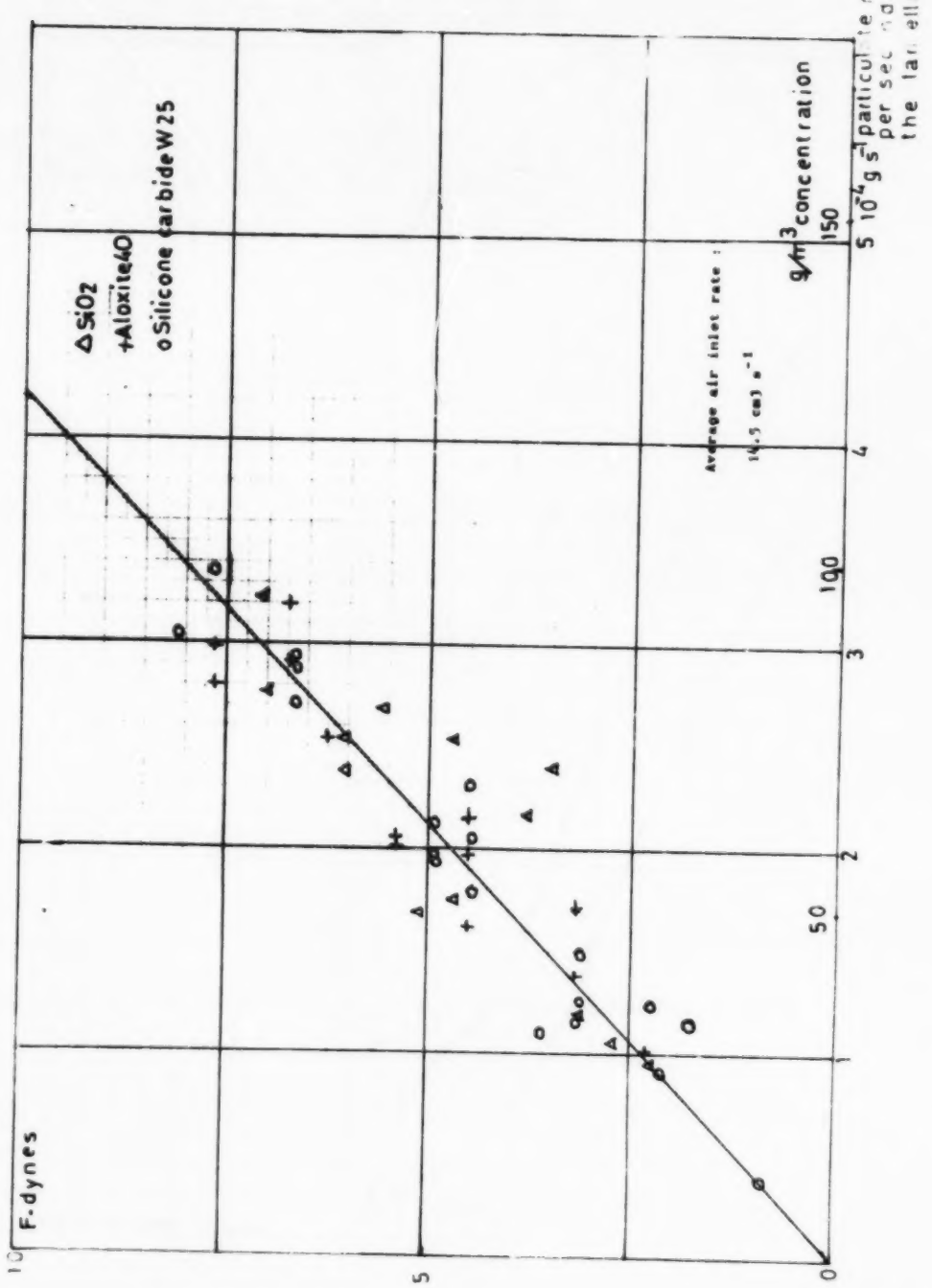

Figure 21. Measured force vs. impacting particulate mass for three different test dusts.

were compared. The abscissae are expressed in two ways: as particulate concentration at the sampling orifice and as particulate mass, effectively hitting the lamella, i.e. taking into account the ≈ 23% efficiency. There is no visible segregation of the points which could be attributed to substance or grain size differences. The scatter is due mainly to three reasons: partly reading and parallax errors, but mostly vibration of the receptor surface. This latter error is estimated to be about ten per cent, which may be ever greater at low angular deviations. Finally it is also possible that the particulate beam velocity varied slightly from one experiment to the other.

3.1.2.4.1 - The influence of the nature of the particulate. The experiment exposed above and summarized in Fig. 21 was repeated with all the particulates of which the grain sizes were given in the Figs. 6 and 11 to 20, measuring ten to thirty concentrations for each. The total of 253 points shows the same regression line:

$$F \text{ (dyne)} = 2.38\ 10^{4} \text{ (cm s}^{-1}\text{)} \quad q \text{ (g s}^{-1}\text{)} \qquad (10)$$

where q is the particulate mass impacting on the target per second; with a regression coefficient of 0.67, highly significant at the quoted 25‰ D.L. level.

The same experiment, with the same apparatus was repeated with coal dust, carbon black, asbestos dust, dust from power plant electrical precipitator, road dust, lycopodium spores, finely ground sugar, heavy oil spray and water spray. No exact grain

size measurements are available about these particles. The "constant" in Eq. (10) contains in fact the particle velocity and the restitution parameter k, and which is 2.38 10^{-4} for hard, irregular particles, takes the following values other particulates Table 2 :

Table 2

Values of the restitution parameter for various substances

	Values of the constant in 10^{-4} (cm s^{-1})	Observations
Coal dust	2.32	
Carbon black	1.56	Adhering speck observed on the lamella.
Asbestos dust	2.35	
Electrical precip. dust	2.37	
Road dust	2.24	
Lycopodium	2.79	
Ground sugar	2.30	Adheres when wet.
Oil spray	1.90	Thin film of constant thickness observed on the lamella; most of the liquid blown away.
Water spray	1.70	

particulates experiencing high-velocity reflection, show quite similar behaviour. On the other hand, adhering particles show a

k value 0.5 even if they adhere only for a relatively short time and are then blown away (e.g. non - viscous liquids, as water).

4. RESONANT MODE SENSING

4.1 - GENERAL CONSIDERATIONS

By Eq.(4) we anticipate still an other mode of impact detection. If the particles arrive just at the resonant frequency of the springmass-system, a very high sensitivity can be expected in the harmonically filtered output. Such a timing in the arrival is quite difficult to obtain with individual particles but it might be done by clusters.

It was shown by HARTMANN (1939) that a jet of air, issuing from an orifice, contains longitudinal compression waves. Instead of theoretical developments, Figs. 22 and 23 illustrate adequately the phenomenon. Particulate matter introduced into this standing, longitudinal wave-system is a) transported by the jet, b) locally condensed and rarified just as it occurs in case of the "powder figures" of KUNDT, a classical physics-textbook experiment.

This idea was tested with the device schematized in Fig.24 which is a development of the basic one shown in Fig.5. The slotted disc obturates the particulate cloud, but not the air intake. Its rotation was adjusted to the frequency of the spring-mass system (about 2 Hz). Qualitative, preliminary experiments have shown, that a more sensitive detection may be obtained than with direct, uninterrupted beam. After a few more preliminary constructions, this approach was found too fragile and perturbation-prone, and was replaced by clustering by a sonic effect, as

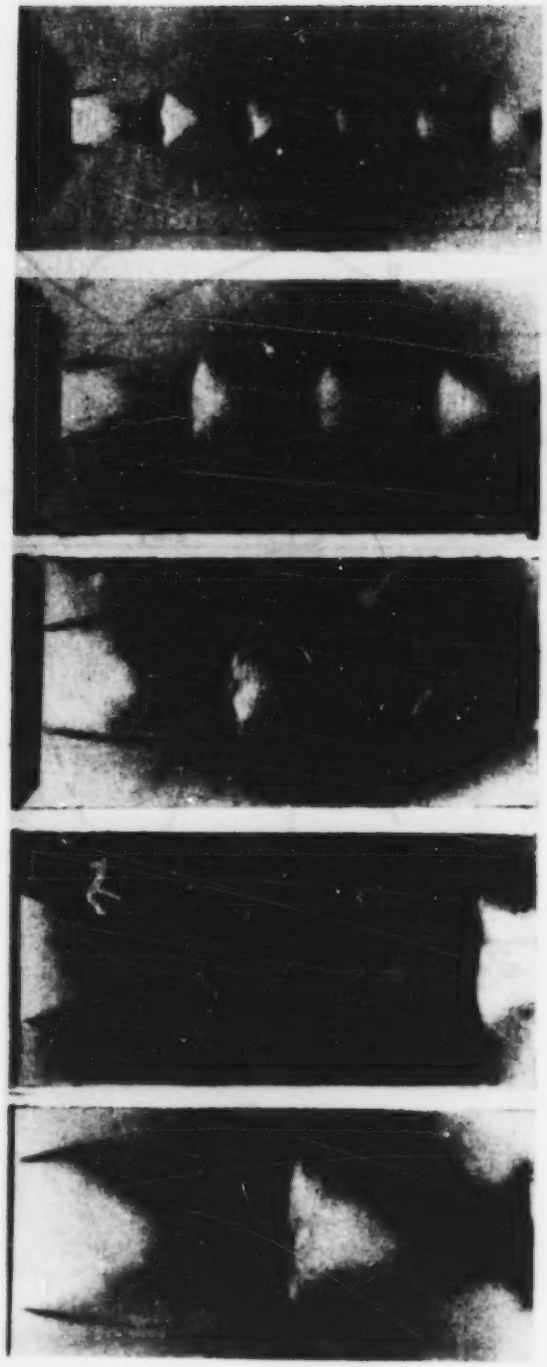

Fig. 22. Structure of pulsating supersonic air jets at different flow rates and orifice diameters. After HARTMANN (1939)

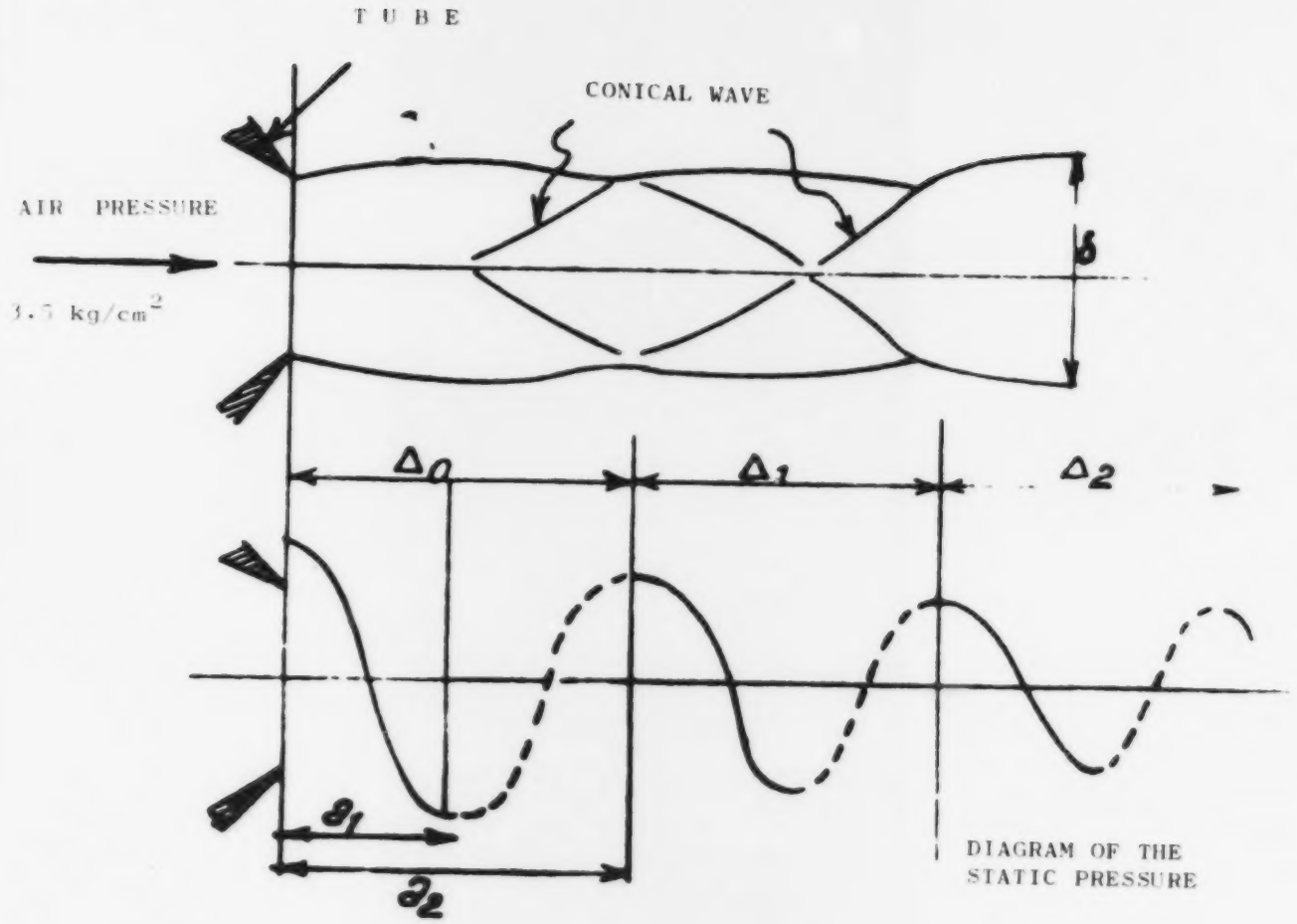

Fig. 23. Schema of air jets with pressure waves.

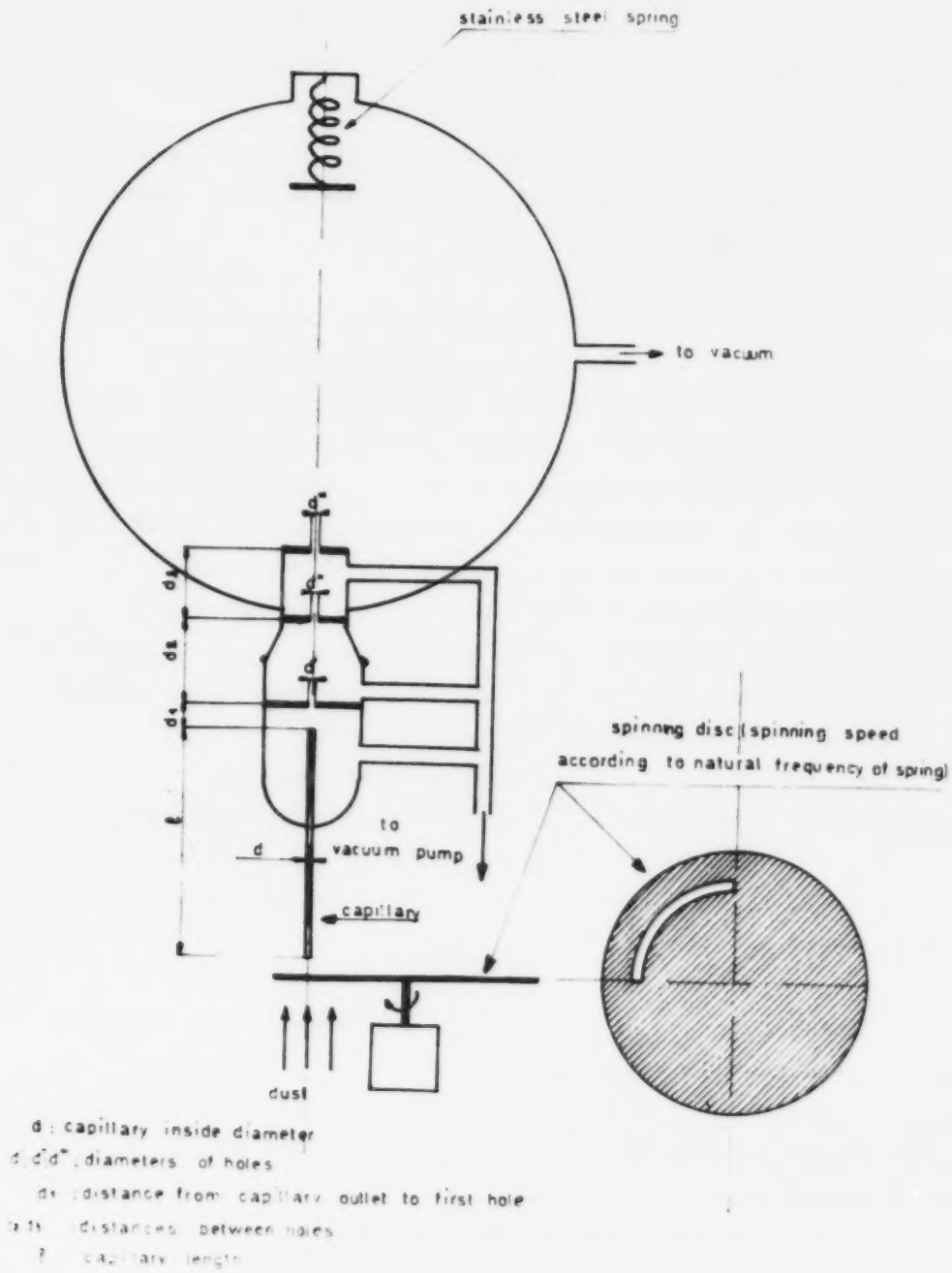

Figure 24. Schema of an early model resonant device.

outlined in the above paragraph.

The schema of the instrument with the vibrating lamella is shown in Fig. 25. The plexiglass envelope allows the observation of the lamella.

The vibrating mode is obtained by adjusting the distance between the lamella and the grounded detector body, from which the particle stream emerges through a critical orifice. Part of this body may be finely adjusted by a differential screw (see Fig. 25). Vibrating mode is not difficult to obtain with (metallized) mica impaction lamellae; but very difficult to obtain with thin metallic foils, as stainless steel. If these are out with scissorlike instruments, the edges are always microscopically bent and the lamella will not be plane. If the lamella is cut by sand blasting or by chemical etching, the release of internal tensions in the (always rolled) sheet warps the lamella by a few microns, which is enough to hinder a successful vibrating mode. Heat-treatment made the metal to loose its indispensable resilience. Very numerous unsuccessful trials were made to obtain good metallic lamellae, before finally settling with mica.

The vibrating mode and the vibration frequency of the lamella were ascertainded in three ways :

1) The vibrating lamella emits a clearly audible pitch. A headphone was fed with a variable sinusoidal frequency from a generator and the two tones matched by the ear.

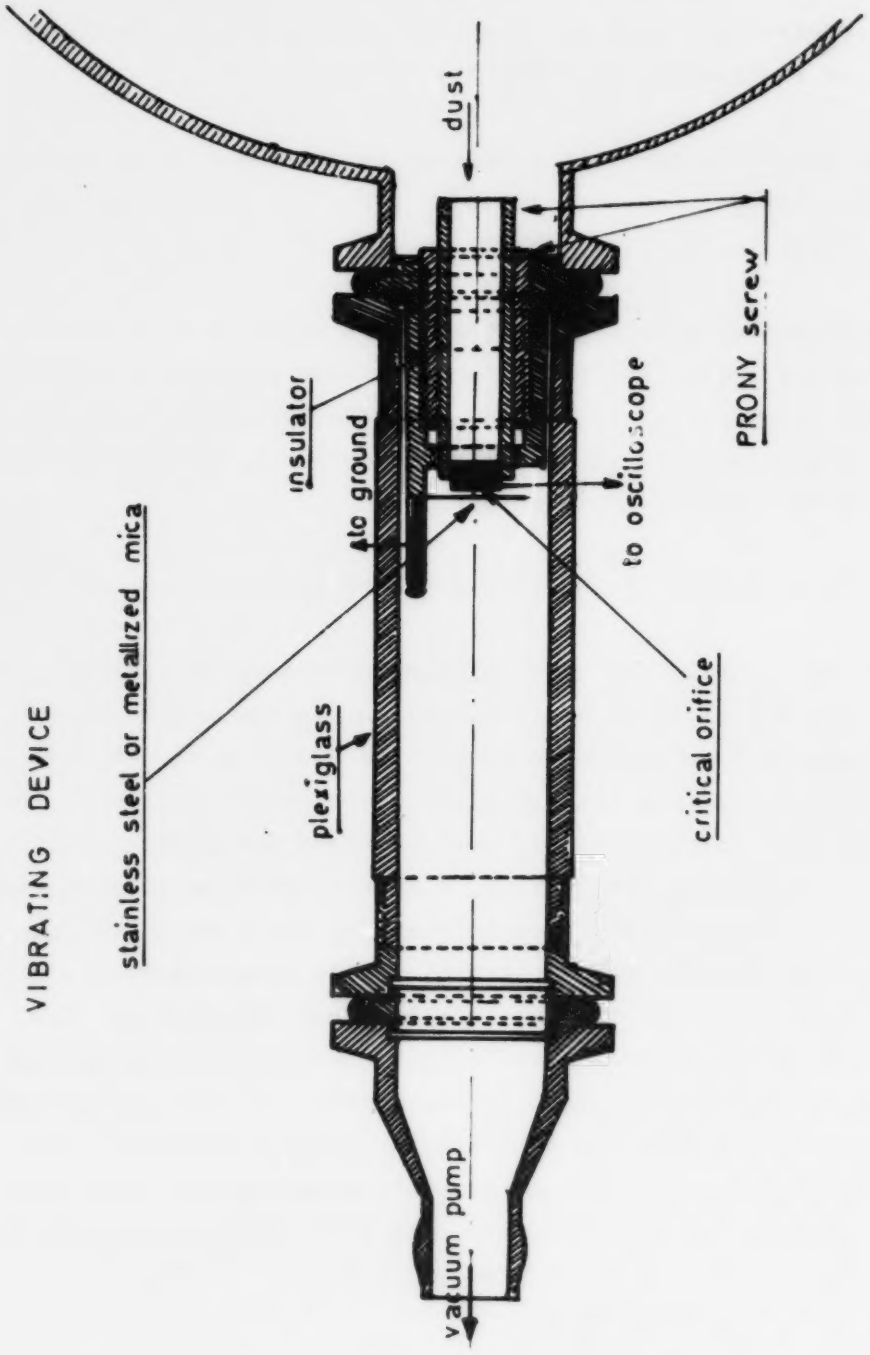

Figure 25. Scale cutoff view of a resonant detector.

2) Through the plexiglass envelope, the lamella vibrations were synchronized with the light of a stroboscope. The "stopping" of the lamella was visually followed.

3) The vibrating lamella, connected to the imput of an oscilloscope, (high impedance, 10 mΩ) gives the sinusoidal response shown in the Figs. 26, 27 and 28.

The frequences measured by these three means were within very narrow limits the same. The amplitude variations in function of the particulate loading are clearly visible with stroboscopic lightning, but as quantitative measuring means, the optical way was not adopted in this case.

4.2 - SOME RESULTS OF THE RESONANT MODE SENSING.

It was seen early, that the resonant mode sensing, while a sensitive way of particulate detection, is not yet a practical one. Before each experiment, the distance of the orifice (detector body) from the lamella must be carefully tuned. The lamella must be plane within a few microns and paralell to the surface containing the orifice, within a fraction of a degree, at least crosswise. In the lengh axis of the lamella the paralellism is somewhat less critical, as its elasticity will allow some adjustement once the vibrations are started, but more than a few degrees slope will hinder the process to start. To sum up the difficulties, it was rather the rule and not the exception, to adjust and to test a "vibrating detector" two days for half an hour of satisfactory measurement. Then, more often as not, the vibrating mode was lost, perhaps because of

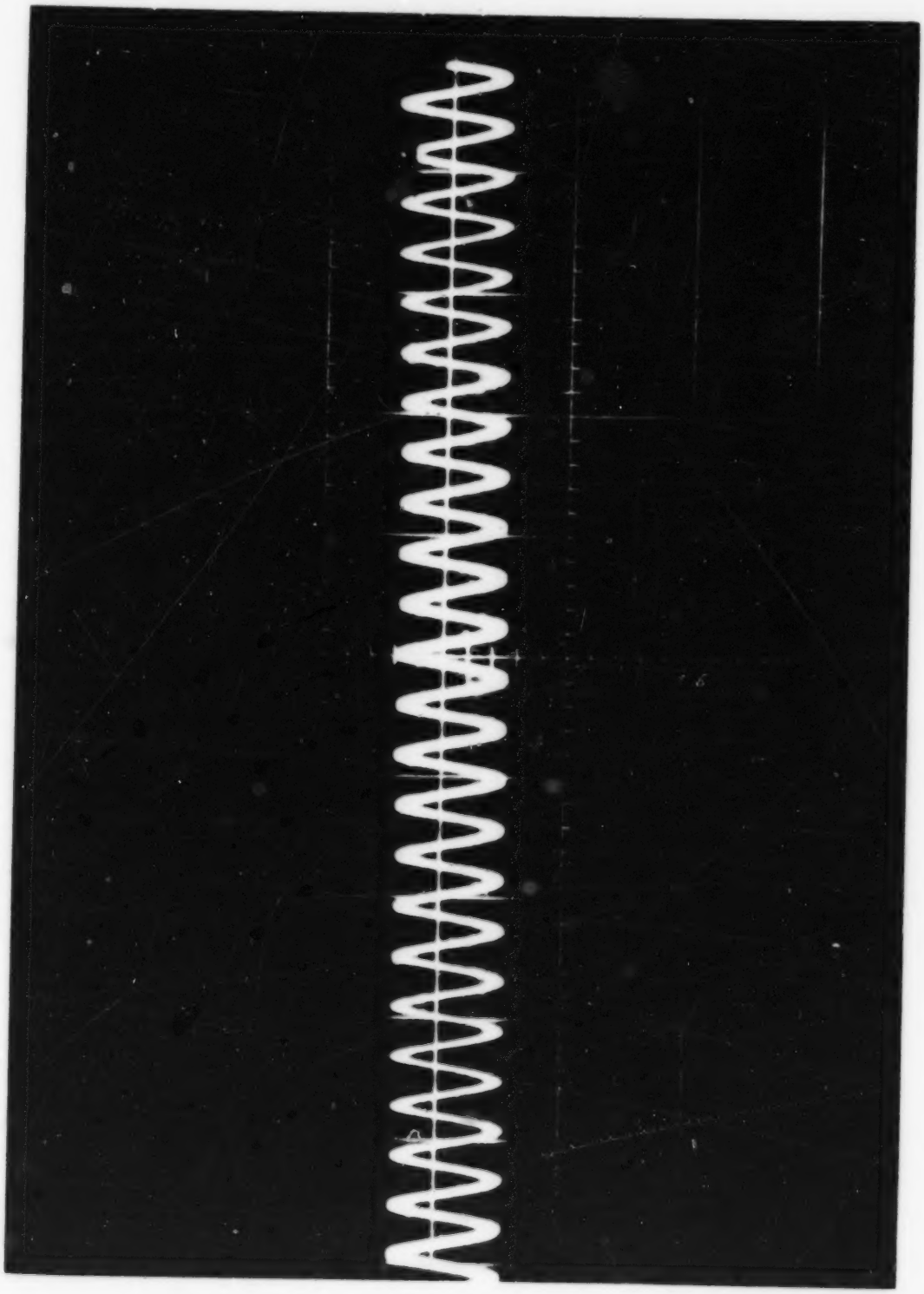

Fig. 26. Example of sinusoidal response

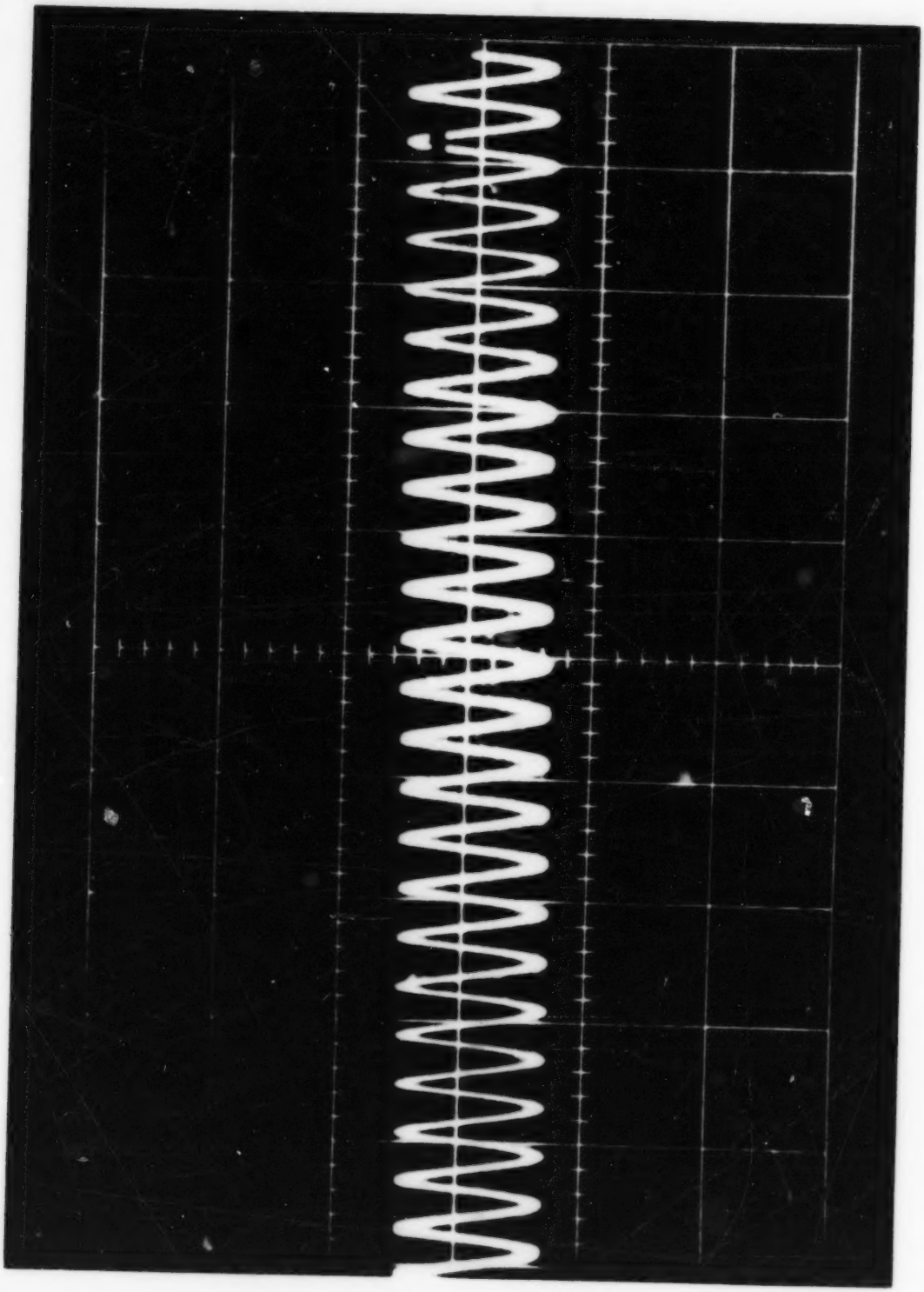

Fig. 27 . Sinusoidal response with 15 mg m^{-3} particulates.

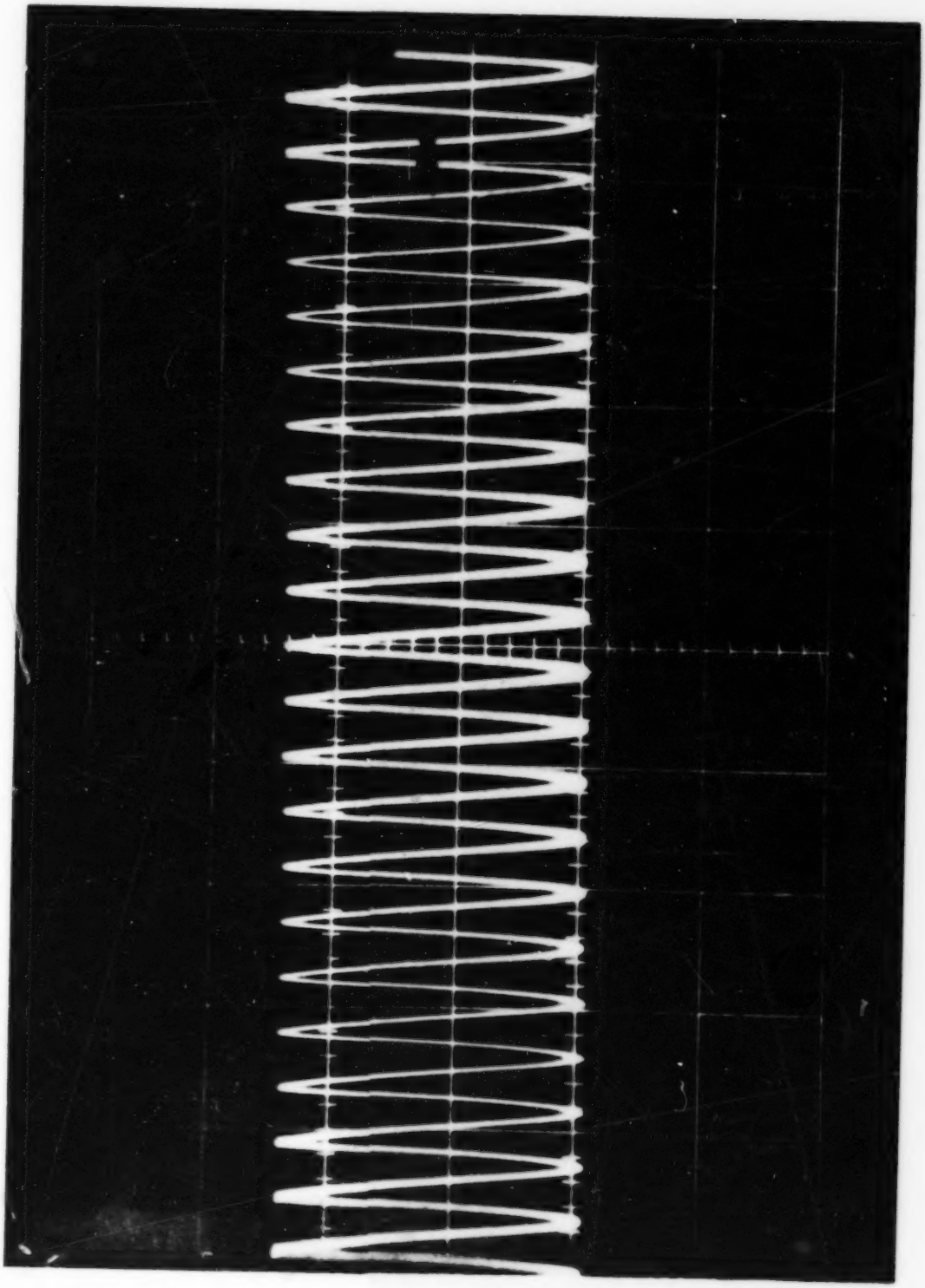

Fig. 28. Sinusoidal response with 30 mg m^{-3} particulate loading

a slight deformation in some part of the device and the "tuning" had to be recommenced. Although, by its sensitivity, this seems a promising device (and perhaps the sensibility may be pushed further by synchronous detection) it is still not technically mature.

A series of results are given in Fig. 29. The amplitudes, as in Figs. 26, 27 and 28 (and others, not presented here as oscilloscope recordings) are plotted against the particulate concentrations, monitored by the SAPHYMO-IRCHA β-ray apparatus.

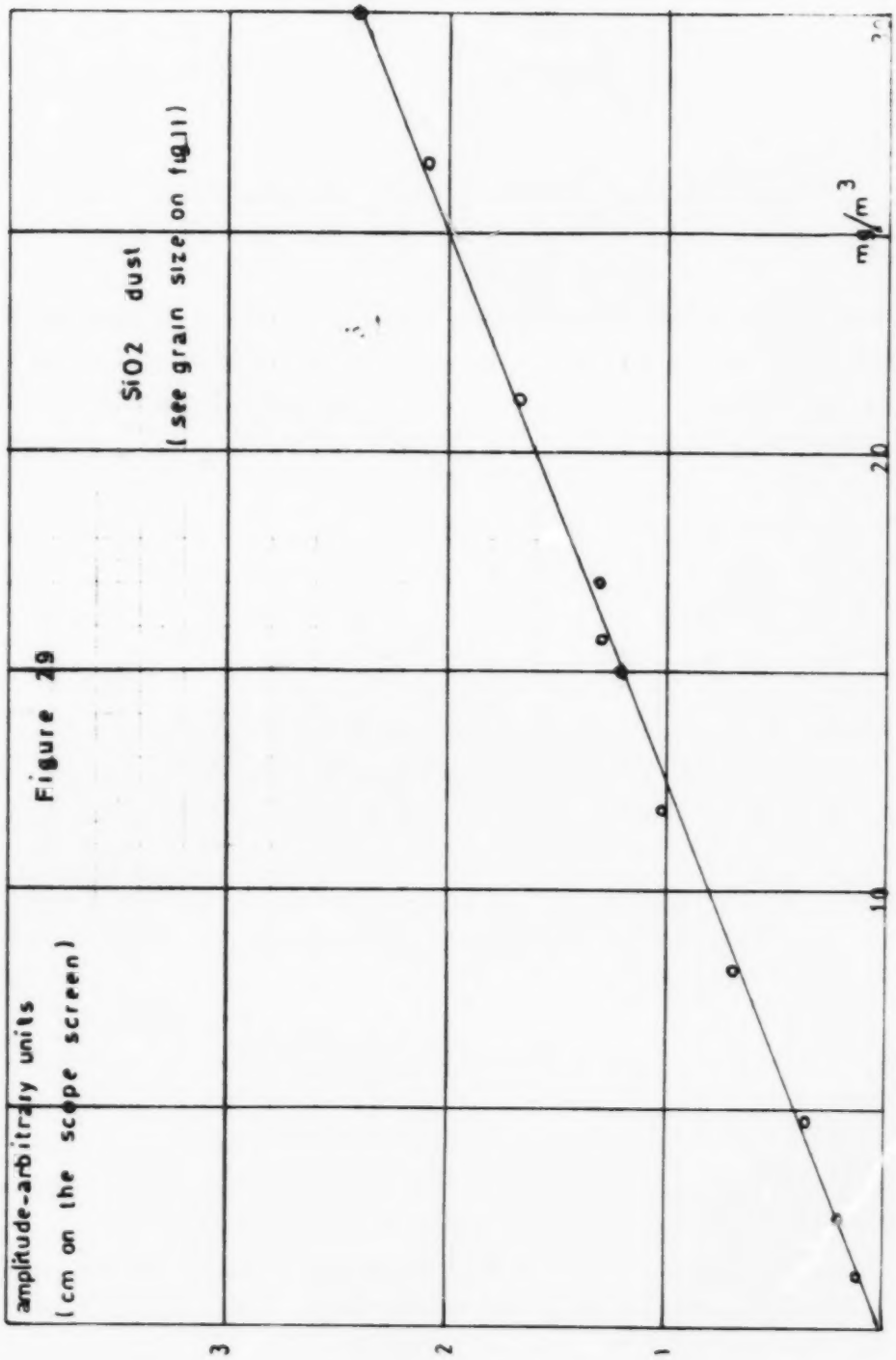

Figure 29. Amplitude vs. concentration for silica dust with a resonant type detector.

5. IMPACT SENSING OUTSIDE PARTICULATE BEAM CONDITIONS

With a relatively short nozzle - generally with a length/diameter ratio of 10 or less - the necessary conditions for the particulate beam formation were not realized. The velocity attained by the particles will neither be uniform nor independent of their grain size. The particle velocities will not approach sonic velocity; they will be rather around a few tenths of ms^{-1}, carrying lesser impact momentum. Nevertheless, their detection is feasible, provided a sufficiently sensitive device exists.

A device of this kind might be produced by a very thin lamella, on condition that it should be quite near (a few tenths of mm) the intake nozzle. The lamella together with the nozzle body thus forms a condenser, the capacitance of which is a function of the distance separating the lamella from the body. Other kinds of proximity sensing (magnetic, inductive, etc..) were also experimented with.

The problem to be solved is the maintaining of a thin, flexible lamella, very near albeit not in contact with a surface. This is hard to do because of a nozzle traversing the said surface and from which a high-velocity particle stream is spurting. A possible solution was suggested by BENARIE and QUETIER (1970). A surface is attracted to an other if an airstream is blown from a central nozzle into the space separating the two surfaces. The air has the highest velocity in the circular zone

around the nozzle and decreases with increasing radius. As on the rim and on the outside surface the pressure is ambient, a depression must be found (ECK 1957, p.27) in the high velocity zone. The effect of this depression is counteracted by the dynamic pressure in the center and eventually by the weight or a spring-loading of the surface. Vibrations caused by this effect, when the damping of the surface is weak, are well known in any plumbing systems' taps.

The system is seducing by its constructive simplicity. Its potential for particulate matter detection, in the ten-to hundred milligram per cubic meter range, was demonstrated. Nevertheless, compared to the technically more exacting particulate beam impact sensing, its several drawbacks should also be noted :

(1) The particle trajectory, albeit very short, does not occur in vacuum. Behind the nozzle acting as critical orifice, about half of the atmospheric pressure is maintained. This fact in addition to the shortness of the nozzle, induces a grain size-sensitivity of the output.

(2) The nearness of the sensing lamella to the earthed detector body, makes any kind of proximity detection easy, but at the same time, because of electrically charged particles, very parasite-prone. It was observed in some cases that electrical charges accumulating on the lamella, obviated the possibility of capacitative detection.

(3) The low particle velocities which may be attained in relatively short nozzles, restrict the impact momentum and in consequence, the lower detection limit.

(4) The abovementioned problems, concerning nozzle and resistance, coupled perhaps with other less known parasitic effects, foreclose the use of the devise in its present form for mass-monitoring. Individual calibrations become unavoidable.

6. INFORMATION ABOUT PARTICLE ADHESION AND BOUNCING

In this section, we will discuss the important factor k of Eq. (1): the momentum transfer parameter.

It is well known from jet impactors and conimeters operating at fairly high speeds, that particles rebound from the receiving surfaces if those are not adhesive-coated (BIRSE and ROBERTS, 1948; JORDAN 1954).

Some experiments on particle collection efficiency (= adhesion probability) were carried out with WO_3 aerosols of 0.013 - 0.018 µm mass median diameter at 200 ms^{-1} by ISRAEL (1967). He found that about 75% of the WO_3 particles were reflected from the formwar or carbon coated electron microscope grids. When the target was covered with a thin layer of silicone fluid, the number of reflected particles was less than 7%. ISRAEL concludes that even very small particles are reflected to a high degree from a target, unless this surface is coated with an adhesive.

A theoretical approach to particle adhesion in beam condition ($v > 100$ ms^{-1}) colliding with a target surface, was made by DAHNECKE (1971). His conclusions were that at velocities of this order, hard, rigid impaction surfaces, as well as thin, flexible membranes will reflect silica and similar particles above 1 µm diameter.

HOLLANDER and SCHORMANN (1974b) provided results of measurements on single aerosol particles of various origin, bouncing from different surfaces. Latex particles show elastic rebound

for velocities < 50 ms^{-1}. For increasing velocities the inelastic losses during the impact increases in such a way that the rebound velocity v_f is nearly constant and independent of v_i the incident velocity. The velocity v_f does not depend significanly on the particle diamter D for .5µm < D < 2.02µm. There is no significant difference between different hard targets (e.g. polished brass and glass).

Irregular shaped particles from crystalline solids (coal, SiO_2, Asbestos) also rebound but have a larger spread in velocity. This is probably caused by the different deformation energy due to different contact conditions and the different amount of rotation energy.

With plastic coated microscope slides, the thicker the film, the faster is the rebound velocity of the particles, regardless of their size, shape and material. This "mattress" - effect can be explained by the fact that the deceleration during impact is less and stress is distributed over a larger area, both effects resulting in a reduced plastic flow.

Liquid DOP droplets and soft carnauba wax particles did not rebound for initial velocities > 220 ms^{-1} but adhered to all tested targets. DOP droplets burst during impact; parts of them are possibly scattered into all directions.

Crystalline materials rarely adhere on smooth, cleaned surfaces when they have irregular shape (adhesion probability, A ≈ 5%). Spherical latex particles practically always rebound.

Adhesion significantly increases (A ≈ 50%) for the combination of an irregular solid particle and coated surface. Coating with vacuum grease retains practically all particles regardless of the shape.

Some results obtained by HOLLANDER and SCHORMANN are abstracted in the following Table 3.

Table 3

Information about rebound properties of particles. After HOLLANDER and SCHORMANN (1974b)

Aerosol	Target	Number of experiments	Mean rebound velocity at $150 < v_i < 300 ms^{-1}$	Adhesion probability (%) estimated
Latex 1.1 µm	clean microscope slide	48	79.1 ± 0.2	< 1
Latex 2.02 µm		50	76.5 ± 0.7	< 1
Coal		29	69.7 ± 1.7	5
Asbestos		58	60.2 ± 2.6	5
Carnauba wax 1.1 µm		60	-	100
DOP 1.1 µm		16	-	90
SiO_2 0.62 µm	polished brass	22	56.4 ± 2.5	5
Latex 1.1 µm	matted glass	13	-	not measurable
	Coated microscope slide	42	133 ± 0.4	5
Coal		43	70.8 ± 2	50
Asbestos	silicon grease	57	-	100

* A cleaned microscope slide once immerged into a 4 % polyisobutylene solution in toluene

During our own experimentation with solid dusts, no deposit was observed on the lamella, even after protracted impacting. On the other hand, with very hard particulates (e.g. Al_2O_3) erosion on the target became visible. With thin ($\approx$ 10µm) lamellae, this effect may continue until neat perforation of the target. That means that in some cases at least, disruption of the target material is possible by the particle beam- a not at all surprising phenomenon after all that is known about technical sandblasting.

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